Parametric Design Principles applied to NZEB in cold extreme climate conditions

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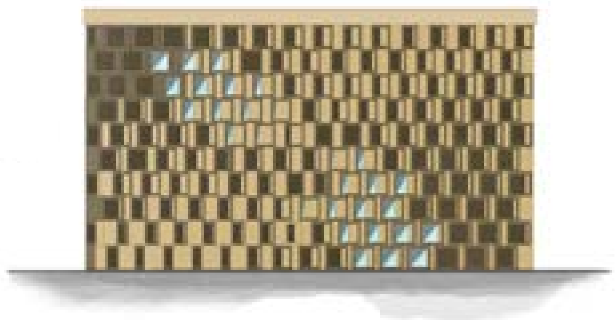
PARAMETRIC DESIGN PRINCIPLES APPLIED TO NZEB IN COLD EXTREME CLIMATE CONDITIONS



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I. ABSTRACT

The master thesis aims to apply the parametric design principles to develop the Zero Emission Building (ZEB) concept for a single-family house placed in Oslo (Norway). This pilot project was developed by The Research Centre on Zero Emission Buildings in Trondheim. It is a simple box-shape two-storey house designed according to the ZEB-OM standards. In accordance with the ZEB Centre's classification, a ZEB-OM is a building in which the produced renewable energy balances the carbon emissions derived from operation and production of its materials. In that regards, the master thesis was focused to develop an integrated workflow to conduct both environmental and energy analyses. It allowed to evaluate the emissions in atmosphere and the energy demand of the building in each stage of the design process. In that sense, the workflow was developed by graphical algorithm editor such as *Grasshopper* (GH) combined with solar dynamic simulation tools, like *DIVA for GH* and *Ladybug*, in order to estimate solar radiation and daylight factor as well as to conduct life cycle assessment. The developed workflow permitted to parametrically control several numeric parameters (i.e. height, width, length, layers' thickness, materials' lifetime, etc.) to vary the physical dimension of building's shape, construction's elements (i.e. walls, roof, windows, slab, etc.) and materials' properties. It led to the continuous generation of the most environmentally responsive shapes always compared to the base case (original ZEB pilot project). The consequent evolutionary lineage describes the possible building's shape distinguishing two different approaches. In the first approach, the passive strategies like exposure, windows' size and position, and type of materials were optimized. While, the second approach was focused on the optimization process for active strategies such as building's shape and use of renewable energy's sources, like building integrated photovoltaic system (BIPV) and algae panels. In this way the initial original ZEB pilot project was modified in order to generate the most environmentally responsive configuration by varying the numeric parameters through evolutionary solvers such as *Galapagos* and *Octopus*. For each stage of the optimization process, it was estimated the emission balance for the final optimized model by calculating the achieved ZEB level and by defining additional strategies in order to reach the ZEB-OM level. The ZEB-OM level was reached on each stage of the optimization process by combining the active systems with the passive strategies.

Keywords: *Residential, Responsive architecture, Embodied and operational missions, ZEB level, Evolutionary computing, Parametric design, Optimization, Solar radiation, Life Cycle Analysis, Daylighting, Energy demand, Building integrated photovoltaic system, Algae façade.*

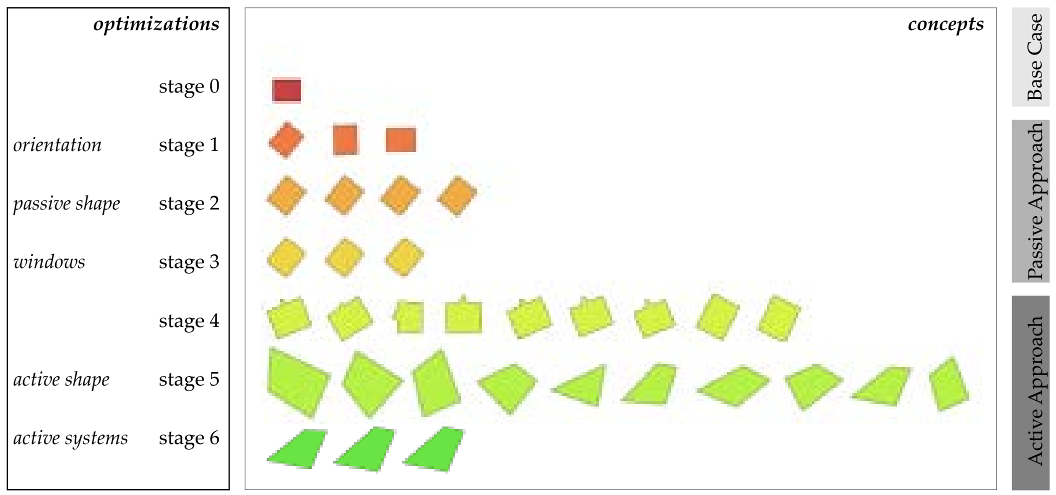

Figure 1 Formal research about the building's environmental responsive configurations.

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1.1.1 Introduction

The environmental impact of buildings on the global energy demand and on the emissions in atmosphere has rapidly increased during the last decades as demonstrate by several studies such as the ones developed by Peters and Riebesel [1,2]. It leads to the evaluation of applying renewable energies sources and alternative technologies to the buildings in order to reduce their ecological footprint. Towards this direction, the Norwegian Research Centre on Zero Emission Buildings (ZEB) in Trondheim is working on developing new solutions to be largely applied on existing and new buildings. They are working on different types of buildings focusing on the dwelling, in particular on the dethaced houses, which represent the more widespread construction's category as shown on Figure 2 (Statistic sentralbyrå, 2015). They are generally timber frame houses with a height that varies from 1 to 2.5 storeys. Approximately 60 % of these were built between 1960 and 1990; therefore they don't have the technical components to guarantee the actual energy targets regulated by the Norwegian buildings regulations, TEK10. The master thesis is focused on a pilot project of a two-storey house that represents the commonest dwelling in Norway. This concept has been already developed by the ZEB Centre and a calculation of its emissions balance is presented on the annual reports about the pilot project state of art [3,4]. On these documents, the research is focused on the emissions assessment taking into account both the embodied and the operational emissions. The building has been planned as an all-electric concept and its energy demand is partially covered by the production in situ of a photovoltaic system and solar thermal collectors. The ecological footprint of this model is influenced by a lot of factors such as the model's orientation, the envelope's geometry, the materials used, the windows size and arrangement. Their variations could modify not only the final visual layout but also its total carbon emissions. This research aims at analyzing the LCA variations depending on the different active and passive strategies applied and the parameters set: from the building's orientation to the active systems placement, from the envelope shape to the rooms arrangement. Actually, the evolutionary lineage of the base case model that is described in this research starts with the improvement of the passive strategies applied. The orientation has been modified in order to have a better exposure, while the materials have been selected taking into account their embodied emission and thermal properties. The parametrization of the façades has represented the first approach to the envelope's redesign that results in the change of the building shape. It allows to improve again the exposure and increase the efficiency of the active systems integrated on the shell such as the photovoltaic cells and the algae panels. The building shape as it appears is the result of complex analyses and choices evaluated by the architect during the planning. The parametric design theory admits the centrality of parameters on the design process: the geometry is founded on numbers and through them it is possible to generate infinite layouts. The employment of Grasshopper (GH) and its generative algorithms permits to modify and analyze the building envelope at the same time; the geometric output has been coupled with a group of components for energy and environmental evaluations. On this process of evaluations, comparisons and improvements, it is important to elaborate a great quantity of data in order to analyze as much configurations as possible. This is important to assume reliable results. The introduction of the evolutionary solvers must be considered from this point of view, they allow to assess several combinations of factors in order to optimize another parameter. Some components of GH such as Galapagos and Octopus work in this way applying the "Darwinian Theory" about the natural selection to the problem solving. The core of this master thesis is the application of this theory on

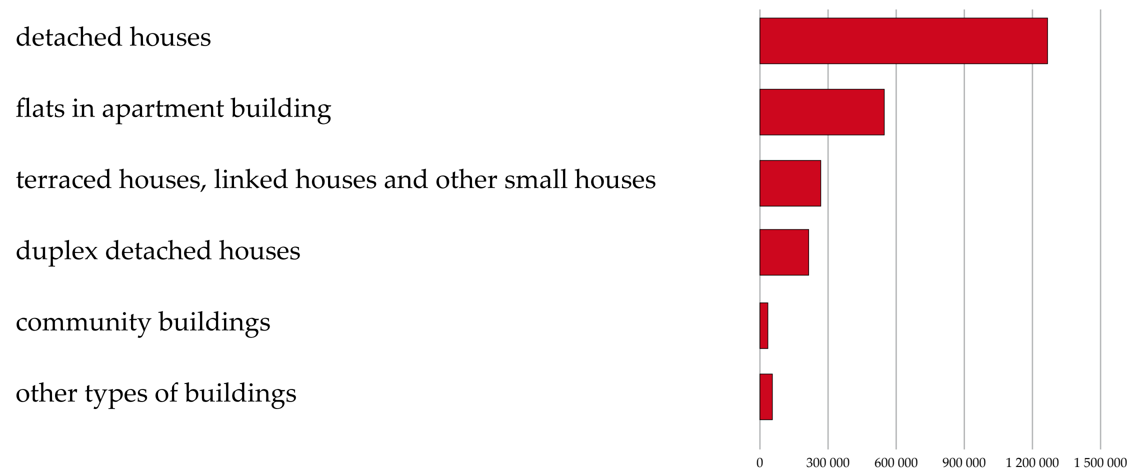


Figure 2 Norwegian house statistic (Statistic sentralbyrå, 2015)

ambition level	phases of the building included in the calculation
ZEB-O EQ	E_o excluding plug loads (i.e. electric appliances)
ZEB-O	E_o (operational energy)
ZEB-OM	ZEB-O + E_e (embodied energy)
ZEB-COM	ZEB-OM + construction phase
ZEB-COME	ZEB-COM + end of life phase
ZEB-COMPLETE	complete life cycle analysis based on NS EN 15978 (CEN, 2011)

Figure 3 ZEB levels on the basis of the ZEB Centre's classification.

buildings to describe its “natural” selection towards the best form in each stage. Each time that the environment changes, the strongest organisms survive. Similarly, the optimization changes its focus step by step and the most responsive dwelling is selected. The consequent evolutionary lineage should lead to an improved concept, the most appropriate for the environment considered. The buildings properties as materials, shape and exposure are managed through a set of input parameters on Grasshopper’s algorithm. For the main output geometries, the ecological footprint was estimated in order to understand the ZEB level achieved in accordance with the classification introduced on the Georges’s research about life cycle emissions analysis of two nZEB concepts [5] and summarized on Figure 3.

1.1.2 Research questions

The research questions investigated on this master thesis are the following:
- How some building’s properties and elements can influence not only its embodied emissions but also its operational emissions;
- Which level of emissions, the improvement of both passive and active strategies can lead to;
- Whether the parametric approach can be considered an adequate method to develop a ZEB;
- How the latitude and the climate conditions can influence the optimized building’s shape and the SR caught by the envelope in general.

1.1.3 Statement of the problems

The two-storey house model represents a project of a dwelling which aims at achieving a ZEB - OM level. It means that renewable energy produced compansates for greenhouse gas emissions from operation and production of its building materials. The concept was just planned considering the state of art of the employed technologies and no effort was made for optimizing the exposure or the choice og the material. Not even the parametric design approach was employed, although it is largely applied on other recent project due to its particular design strategies, for example the Zero Emission Design (ZERO-E) developed by Woods Bagot and Buro Happold [6]. On the basis of the “parametric view”, the architecture is only the visual consequence of numeric input values such as the coordinates of a point or the radius of a circle. Their variation permits to have thousands models based on the same concept. The alternatives can be explored thanks to evolutionary solvers as Galapagos and Octopus. They are specific tools which apply the “Darwinian Theory” in order to optimize the chosen fitness along the “evolution” of the building. In conclusion, the combination of the shape’s optimization for the pilot project of zero emission building, through the parametric design and the applied evolutionary theory represent the three main fields of research explored on this thesis.

1.1.4 Background and needs

The development of a new concept starts from a correct and detailed analysis of the base case. It permits to have an idea of what it is necessary to develop and how. The organization of passive and active strategies, and the definition of their respective boundaries are important for the planning of the workflow. The needed improvements are related to the embodied emissions, operational emissions and PV production, which are the three categories considered for reaching the ZEB - OM ambition level as previously explained. The shape of the dwelling and of its envelope in particular, influences the quantities of materials employed and the energy demand too. The analysis of the solar radiation (SR), instead, permits to optimize the production from active systems such as PV, BIPV or algae panels.

1.1.5 Purposes of the study

The main goal of the research is to study the variation of the carbon emission due to the different input parameters trying to improve the base case model stage by stage. The resulting final model should be better than the original and permits to achieve the ZEB - OM ambition level with an all-electric concept. The use of evolutionary solvers should allow evaluating the possible combinations of parameters so that the result turns out to be more reliable. The solvers are able to select the best genes and combine together for reaching a more responsive configuration. Anyway, the focus of the thesis is on the method employed for achieved the betterment of the base case and not on the shape, the ambition level achieved or the results. In conclusion, the main goals of this thesis are summarized on the following three points:
- Parametric design theory applied to ZEB pilot model in Oslo;
- Improvement of passive and active strategies;
- Assessment of LCA variations depending on different design approaches.

1.1.6 Topic

The overall overview of the topics treated in this thesis is:
- Parametric design for evolutionary theory
- Building optimization
- Zero emission building
- Passive and active strategies
- Solar radiation analysis
- Daylighting assessment
- Embodied emissions calculation
- Operational emissions evaluation
- Building energy demand and energy production in situ
- Building integrated photovoltaic system
- Responsive architecture
- Algae panel
- Emission balance and ambition levels

Figure 4 Zero Emission Design (ZERO-E) is a new carbon neutral and sustainable program developed by teams Woods Bagot and Buro Happold.

2.1 ZERO EMISSION BUILDING

2.1.1 Introduction

Several studies estimated that commercial and residential buildings are responsible for the consumption of around 40% of primary energy and for releasing 24% of greenhouse gas emissions in Europe [7]. It brought the European Union to the introduction of new standards, the Energy Performance of Building Directive (EPBD, 2002), to achieve the reduction of buildings' energy demand. It represents the first step toward the improvement in energy performance of Member States' constructions. The current version of EPBD was released on 2010 and states that each European Country should make certain that all the new buildings for public authorities and properties would be able to reach the Net Zero Emissions Building (nZEB) ambition level by 31st December 2018. On the other hand, the new buildings in general should guarantee the same quality level by 31st December 2020. The D'Agostino's research [7] starts from the evaluation of this document and its definition of nZEB in order to analyze what way that concept has been integrated on national technical regulations. In fact, nZEB are defined as buildings that "have a very high energy performance with a low amount of energy required covered to a very significant extent by energy from renewable sources, produced on-site or nearby". Nevertheless, D'Agostino observes that a limit value such as the height of energy performance's quality level or the amount of renewable energy's contribution, has not been introduced on the previous definition. That gap on European regulations obligates each Member State (MS) to consider a concept of nZEB appropriate to its country. The overview of all those guidelines represents the core of D'Agostino's studies. Otherwise, only the Norwegian and Italian policies for nZEB will be considered on this master thesis. The 2015 report of Building Performance Institute Europe (BPIE) [8] shows the state of development of national policies for energy efficiency, renewable energy and energy performance of European buildings, focusing in the state of the definition of nZEB for the EU28 plus Norway. The results are summarized on Figure 5 and highlight that Norwegian definition is still under development, while the Italian one is just waiting to be approved. The Norwegian government started introducing the concepts of passive houses and low-energy buildings through the technical regulations for building planning: NS3700 for residentials and NS3701 for other constructions. The first is examined more in depth on the specific paragraph. The Norwegian definition for ZEB is based on the work of the national Research Centre on Zero Emission Buildings (ZEB Centre) in Trondheim that aims at eliminating the greenhouse gas emissions caused by buildings. It presented several categories of ZEB depending on how many phases of the building's lifetime have been considered. The main classes are ZEB-O EQ, ZEB-O, ZEB-OM, ZEB-COM, ZEB-COMPLETE. They are summarized on Table 1 and Table 2. Although this is the classification that we are going to use on this thesis, it is not the only one existent. On the following lines it is reported an overview of definitions of nZEB performance levels. According to Panagiotidou [9], the term ZEB could be used in reference to residential or commercial buildings that achieve the reduction of energy needs and carbon emissions through efficiency gains, such as the supply of renewable energy. Laustsen's research [10] distinguished ZEB in two categories: Autonomous ZEB and Net ZEB. The first type does not need to be connected to the grid because buildings included in that class are able to store energy for when it is not possible to generate it. The Net ZEB is a yearly energy neutral building, a construction which consumes as much energy as produced by renewable sources during a year. In other words, it delivers to the grid as much energy as it has been taken. If the energy introduced into the grid is more than the power import through a year, the house reaches the level of Energy Plus Building. Torricellini et al. [11] proposed a subdivi-

category	description
ZEB-O EQ	renewable energy produced compansates for greenhouse gas emissions from operation except the energy use for equipments
ZEB-O	renewable energy produced compansates for greenhouse gas emissions from operation
ZEB-OM	renewable energy produced compansates for greenhouse gas emissions from operation and production of its building materials
ZEB-COM	renewable energy produced compansates for greenhouse gas emissions from construction, operation and production of its building materials
ZEB-COMPLETE	renewable energy produced compansates for greenhouse gas emissions from the entire lifespan of a building

Table 1 Description of the ZEB level defined by the ZEB Centre in Trondheim depending on the building's emission balance.

	materials	construction	energy for equipments	operation	demolition and recycling
ZEB-O EQ				■	
ZEB-O			■	■	
ZEB-OM	■		■	■	
ZEB-COM	■	■	■	■	
ZEB-COMPLETE	■	■	■	■	■

Table 2 ZEB classification depending on the phases of the building's lifetime considered.

sion of ZEB in four categories depending on boundaries and metrics, among these, the Net Zero Site Energy Building indicates a group of elements which are able to produce at their location at least the amount of energy they need. In Lund et al. [12], four different types of ZEB are distinguished in reference to energy demand and installed renewable typology. For instance, PV-ZEB defines a building with a relatively low electricity demand and a photovoltaic system (PV), while the Wind-ZEB would employ a small on-site wind turbine to supply electricity to the house. Other categories have been created which evaluate the possibility of combining several sources of renewable energy, such as PV-solar thermal-heat pump ZEB or wind-solar thermal-heat pump ZEB. Thus, there are different classifications due to a lack of regulations about ZEB: an European common definition has not been introduced yet. Thus, the categories proposed by the Research Centre on Zero Emission Building of Norway have been considered to define the performance level achieved on the concepts designed in this research.

2.1.2 TEK10 and NS3700

The concept of "passive house" was developed by German Passive Haus Institute that aims at increasing the building's quality level through the application of passive strategies such as reducing heat requirements, exploitation of internal heat sources, use of high insulated envelope with minimal thermal bridge and advanced heat-recovery ventilation system. Thus, the passive houses are constructions with energy need lower than current standards so that it was necessary to create specific standards. On 2011, the Norwegian government issued the NS3700, a document that regulates the passive houses planning and defines the different reachable levels. Nowadays, Norway is the only country with a separate standard for this kind of buildings. Instead, the TEK10 is the Norwegian buildings regulation and defines the technical requirements for structures. After the EU Directive 2010/31, the regulations were made stricter regarding the energy performance of buildings. Those regulations could be applied to new constructions or existent buildings for both general renovation and change of use. There are two ways to meet the requirements of energy efficiency: the measure method and the frame method. The first allows to analyse the house taking into account the minimum standard for U-value, the total amount of windows and doors in the façade and the maximum leakage figures. The other one permits to compare the total net energy for building to a limit value. The total net energy is evaluated considering the heated area according to NS3031 standards. The energy limits are set depending on category, size and location of the construction. Moreover the regulations introduce buildings minimum requirements which are shown on Table 3. The NS3700 introduces the concept of passive house into the norwegian building standards: it is described as a building that uses passive strategies to reduce the energy demand. The standards provide a primary energy limit value, calculated on the net space heated, which could be corrected depending on the climate zone, location and size. All the passive houses are divided in three categories: passive, low-energy class 1, low-energy class 2. This classification could be applied to new or existent buildings. Otherwise, the Italian regulations it is quite far from the Norwegian one. There are different limit values for element's thermal transmittance depending on the building location due to the several climatic conditions which characterize the Italian peninsula. They are reported on Table 4, each letter represents a climatic zone. As previously revealed, there are no specific standards for a passive house and all the certifications are released by private research centre. It is not possible to compare the standards because of the different latitudes of the two countries, but it is quite interesting to observe the diverse regulations structures and types of approach employed by the governments to satisfy a citizens' need.

2.1.3 Norwegian ZEBs

A definition of ZEB is still under development in Norway and it represents the main objective of Research Centre on Zero Emission Building in Trondheim. As explained on the studies built up by Houlihan Wiberg et al. [13] and related to Dokka et al. [14], it is necessary to describe clearly this

Figure 5 State of art of the nZEB definition for new buildings on the Member States (BPIE, 2015).

standard for houses		TEK10			NS3700	
		minimum standard	measure method	frame method	low-energy class 1	passive
total net energy	*kWh/BRA/y*			120 + 1600/m^2		
outer wall	*W/m²K*	≤ 0.22	≤ 0.18		≤ 0.16	≤ 0.12
roof	*W/m²K*	≤ 0.18	≤ 0.13		≤ 0.12	≤ 0.09
windows and doors	*W/m²K*	≤ 1.60	≤ 1.20		≤ 1.20	≤ 0.80
ground floor slab	*W/m²K*	≤ 0.18	≤ 0.15		≤ 0.12	≤ 0.08
thermal bridge	*W/m²K*	≤ 0.03	≤ 0.03		≤ 0.05	≤ 0.03
heat exchange efficiency	*%*	≥ 80.0	≥ 80.0		≥ 70.0	≥ 80.0
specific pump power	*kW/m³s*	≤ 2.50	≤ 2.50		≤ 2.00	≤ 1.50
air leakage 50 Pa	*air change/h*	≤ 3.00	≤ 2.50		≤ 1.00	≤ 0.60
ventilation airchange	*m³/m²h*	1.20	1.20		1.20	1.20
window and door area	*% BRA*	≤ 15.0	≤ 20.0		≤ 15.0	≤ 15.0

Table 3 Building minimum requirements. The standards are referred to residential buildings, the category in which the ZEB pilot project optimized in this thesis is included.

climatic zone	outer wall	roof	grounf floor slab	windows and doors
	W/m²K	*W/m²K*	*W/m²K*	*W/m²K*
A	≤ 0.54	≤ 0.32	≤ 0.60	≤ 3.70
B	≤ 0.41	≤ 0.32	≤ 0.46	≤ 2.40
C	≤ 0.34	≤ 0.32	≤ 0.40	≤ 2.10
D	≤ 0.29	≤ 0.26	≤ 0.34	≤ 2.00
E	≤ 0.27	≤ 0.24	≤ 0.30	≤ 1.80
F	≤ 0.26	≤ 0.23	≤ 0.28	≤ 1.60

Table 4 Limit for elements' thermal transmittance in accordance with Italian standards. The climatic zones varies depending on the average annual temperature, from the higher (A) to the lower (F).

type of constructions before proposing solutions and concepts. The main features considered by ZEB centre are ambition levels, rules of calculation, system boundaries, CO_2 factors, energy efficiency, mismatch and indoor climate. As summarized on Table 1, five different ambition levels are defined starting from the lowest, ZEB-O EQ. It indicates a building characterized by zero emission level for operational stage (O) excluding the energy required for appliances and equipments (EQ). The highest value considered on Houlihan Wiberg et al.'s article is ZEB-COM where construction (C), operation and embodied emissions of building materials (M) are taken into account. Actually, it has been recently introduced a higher ambition level, ZEB-COMPLETE, which includes also the demolition and recycling phase. The ZEB-O and ZEB-OM represent two intermediate levels and are the ones investigated on the Houlihan Wiberg et al.'s studies on this thesis. The rules of calculation are referred to the energy demand of buildings which should be evaluated according to the Norwegian office standards for passive houses, NS3700 and NS37001. The building lifetime is assumed to be 60 years. The system boundaries are the following: local renewable energy shall be produced on-site, but off-site renewables can be used in this electricity production. Thermal energy production for the building area can be both on-site and off-site, but it is necessary taking into account the total system losses from production to emission in the building. The reference investigates only an all-electric approach for the energy supply so that the only CO_2 factor introduced is the one about electric mix. Although no official value of CO_{2eq} factor currently exists in Norway, it is possible to assume that Nordic and European grids will be strongly interconnected so that it can be considered an average. Futhermore, a 90% reduction of the CO_{2eq} emissions shoul be achieved by 2050 taking into account the long-term political goals of MS for elctricity production. Thus, the average CO_2 factor for electricity can be calculated at 0,132 $kgCO_{2eq}/kWh$ for a building constructed in 2013 as the research suggests. The building's energy efficiency is defined according to the Norwegian regulations that identify some border values like a minimum for elements transmittance and a maximum for heat losses. In particular, the rules about residential building, which were applied to the ZEB pilot project are explained more in depth at the specific paragraph highlighting all the standards considered. About the mismatch between energy demand and energy produced on-site, it can be evaluated on hourly, daily, weekly or annual basis. The approach used is called the symmetric weighting and permits to employ an constant CO_{2eq} factor for both imported and exported electricity. The indoor comfort should be in compliance with the requirements contained in the Norwegian building code and the ones considered on ISO 7730 about local discomfort.

2.1.4 Living Lab Pilot Project

The Living Laboratory is a single family house built at the Gløshaugen campus of Norwegian University of Science and Technology (NTNU) in Trondheim through the collaboration of students, researchers and industry partners. Started as an integrated design process where students and researchers developed a prototype of an positive energy hytte - a common building typology in Norwegian culture - as a prefabricated modular construction, it has been redesigned as a temporary building. As explained on the presentation of Goia et al. at Passivhus Norden meeting about Sustainable Cities and Buildings on 2015 [15], this facility was designed to investigate the house at different levels, from envelope properties to building equipment components, from ventilation strategies to action research on lifestyles and technologies. House to construct both passive and active design strategies were employed. The energy conservation was integrated with the solar energy exploitation towards a low-carbon architecture. The attention paid to the choice of materials and systems for minimizing the embodied emissions allows to reach the ambition level ZEB - O. It means that renewable energy produced compansates for greenhouse gas emissions from operation. The Living Lab pilot project is located at latitude 63°4' N and longitude 10°4' E, in a site characterized by cold climate conditions. Inman's thesis [16] presents a morphological analysis of the building highlighting its compactness, porosity and slenderness; all of them are morphological traits of bioclimatic houses in Norway. The dwelling is arranged on one storey with a heated surface of approximately 100 m^2 and a volume of 500 m^3. The areas related to this construction are summarized on Table 6 according to Norsk Standard of 2012. The house has been completed in Spring 2015 as a temporary

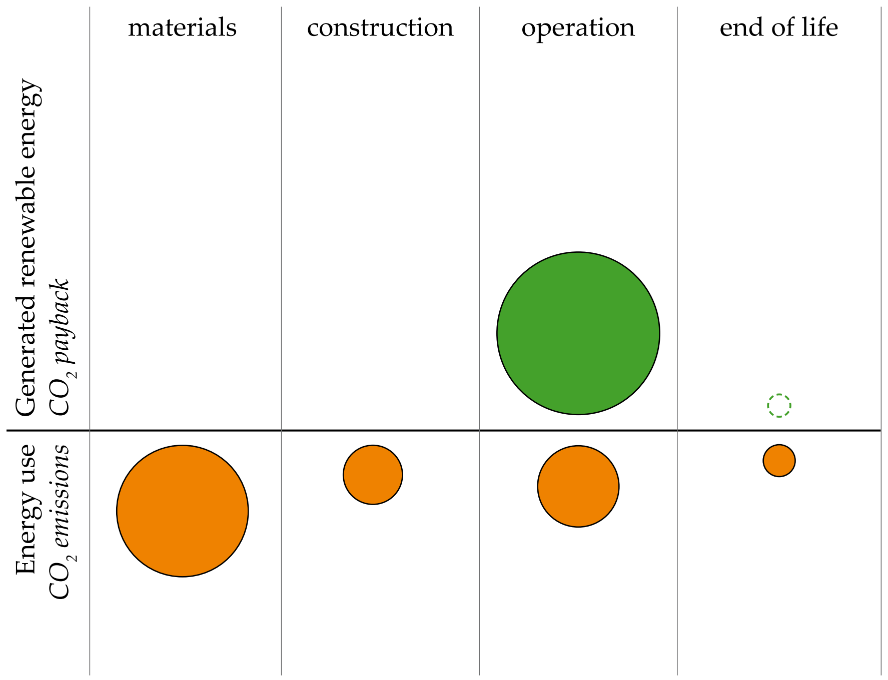


Figure 6 The graph introduces the CO_2 emissions and payback which characterized each stage of the building's lifetime.

Definition	
ambition level	ZEB-O EQ; ZEB-O; ZEB-OM; ZEB-COM; ZEB-COMPLETE
rules of calculation	NS3700; NS3701
system boundaries	electricity: on-site (included production with off-site renewables)
	thermal: on-site and off-site
CO_2 factors	0.132 $kgCO_{2eq}/kWh$ for building constructed on 2013
energy efficiency	NS3700; NS3701
mismatch	symmetric weighting
indoor climate	Norwegian building code and ISO 7730

Table 5 Features considered by the ZEB Centre for defining and comparing the zero emission buildings.

type	abbreviation	area *m^2*
gross floor area	BTA	132
heated floor space	BRA	102
net floor area	NTA	97
built up area	BYA	219

Table 6 Area of the building in accordance with the Norsk Standard of 2012.

demonstration building and its plan is organized in two main zones, the southern as a living space and the northern as a working or sleeping area. All of these are planned so that they can be lived by different users, from youngers to olders, from students to families. It permits to investigate several social levels and their reaction to the new technologies employed. Also for that reason the buildings have been equipped with a great amount of sensor in different zones. The design strategies applied are reported on Figure 7 and Table 7. Both the passive and active strategies try to exploit as much as possible the power of sun to reduce energy demand and producing energy. The compact shape, the southern orientation and the sloped south-facing roof are some of the solutions proposed, but the active approach seems more articulated. It is characterized by the employment of a lot of technologies such as building integrated photovoltaic panels (BIPV) on the roof, solar thermal collectors (STC) on the south façade, phase change materials (PCM) in the roof, double window that acts as a buffer zone, hybrid ventilation with opportunities for cross ventilation, vacuum insulation panels (VIP), geothermal heat pump and dynamic solar shading to regulate solar gain and glare. Since the early stage of the project, the construction has been constantly optimized through several simulations that certified the high level of insulation quality of the envelope. The timber frame structure has been coupled with a double layer of rock wool insulation reaching a U-values of 0.11, 0.10 and 0.11 W/m^{2}K, respectively for walls, floors and roofs. The Living Laboratory Pilot Project has been developed not only to be a typic Norwegian dwelling but mainly a laboratory, as its name suggests. That is the reason which led to the installation of an advanced monitoring system. It allows to collect experimental data and characterize the energy and environmental performance of the building. The sensors are able to monitor indoor and outdoor environmental quantities such as air temperature, humidity ratio and pressure, CO_2 concentration, diffuse illuminance, wind velocity, global solar irradiance on different planes and illuminance. Futhermore, they record the users patterns and the occupants' habits like room occupancy, shading system opening and use of appliances and lighting system. Other sensors work to measure the energy consumed by the building splitting that in five groups depending on the use: heating, ventilation, domestic hot water, artificial lighting and appliances. The system is also able to quantify solar radiation exploitation and energy taken from the grid, so that it can be assessed the efficiency of the building. In conclusion, more than 200 signals are continuously acquired and half of them are sent out from the house level controller to manage the several technologies installed on the construction.

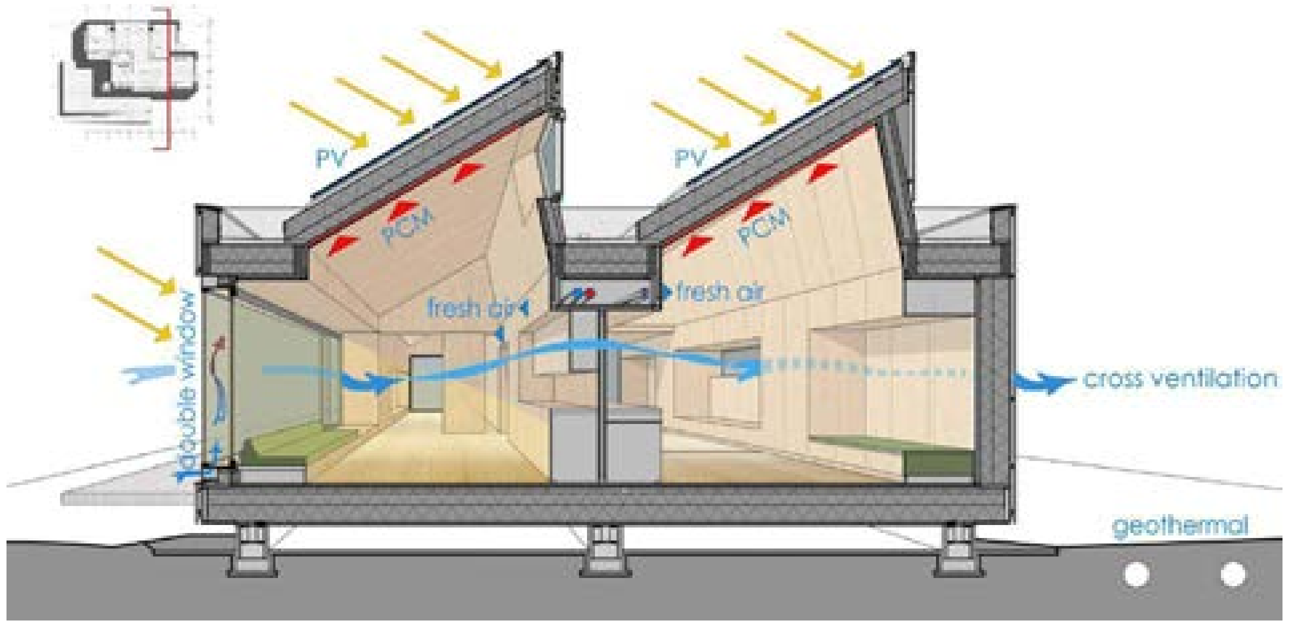


Figure 7 A section of the building that shows the interaction and operation of the strategies applied.

passive strategies	active strategies
compact shape	*building integrated photovoltaic panels*
southern orientation	*solar thermal collectors*
sloped south-facing roof	*phase change materials*
	double window as a buffer zone
	hybrid ventilation (cross ventilation)
	vacuum insulation panels
	geothermal heat pump
	dynamic solar shading

Table 7 An overview of the passive and active strategies emploied on the Living Lab Pilot Project. The employment of several active strategies permits to test the efficiency of different combination of them.

Figure 8 An external view of the building. The South-exposed sloped roof is able to catch the solar radiation and exploit it for producing electricity.

Figure 9 The design of the inner space is simple and in line with the Norwegian tradition. The living room and the beedroom represent the two main spaces of the dwelling.

3.1 INTRODUCTION

The first step on a design process is the definition of the scopes and the path to reach them. The work would seem easier if the procedure will be clear. Moreover, an understandable research's structure should facilitate the readers to comprehend the results and how they were achieved. The following paragraph introduces the concepts behind this master thesis explaining the sections which the work is divided in, with schemes and workflows.

The main goal of the research is to study the variation of the carbon emissions due to the different input parameters trying to improve the base case model stage by stage. To achieve this target, the work has been organized in three parts: literature review, passive approach, active approach. At the beginning, the goals and topics were identified and summarized in few keywords to make research among the existing publications. In this way, a complete overview and a state of art were developed and included on the literature review that has been updated during the whole thesis duration. This part included all the knowledge necessary for the application of the method described on this research. In particular, the application of parametric design to the planning of an environmentally responsive ZEB is realized through the employment of Grasshopper, a plug-in for Rhinoceros. As much analyses as possible were developed in GH environment in order to reduce the need of exporting the geometry towards other platforms. Thus, it was realized a state of art of the main tools for optimization process, environmental analysis, energetic assessments and BIM modelling. Once the tools' potentials were evaluated, the procedure has been defined. Finally, the only analysis which cannot be developed in GH environment is the one for defining the energy demand. Althouhg it is possible to run this type of simulation in GH, it was emploied Design Builder in order to have a better overview of the results. The whole optimization process is developed in GH environment and the approach to the building's changes is organized in two different parts: passive and active approach. Initially, the passive strategies already applied were strengthened and then the active strategies to produce energy were developed. The Figure 10 summarizes the process applied to the otpimization of each model, in fact this path has been followed cyclically in order to model each time a concept better than the previous. The forks highlight the main differences between passive and active approach. On the right column, instead, the outputs for each step are presented in a list. Not all the models generated during this study were analyzed at the same way. An overview of the assessments carried out for each stage of the optimization is reported on Table 8. The Figure 11 shows the features identified and the approach to each one. In particular, during the passive approach the shape and the photovoltaic system are maintained, while the exposure to solar radiation, the consequent rooms' arrangement and the daylighting are optimized. Otherwise, the parametric façade is introduced while the active façade is not yet considered. All the model modifying these features are compared to the base case model considering the building's CO_2 emissions and the quantity of solar radiation caught as well as the energy demand. The optimization of some properties of the constraction is developed using Grasshopper's components as Galapagos or Octopus which apply the "Darwinian Evolutionary Theory" to the problem solving. Although it could be considered as a passive strategy, the shape improvement is considered as a part of the active approach's section because it was introduced mainly to increase the contribution of the active systems present or added (i.e. PV, BIPV, algae panels, etc.). On the last section none features of the original two-storey house is maintained. All the properties considered were optimized or introduced for the first time into the model. As previously written, the shape change and the active façade are evaluated in order to analyze their impact on the ecological footprint defined in accordance with the ZEB ambition levels. All the other properties such as PV systems, solar radiation caught, rooms arrangement, parametric façade and daylighting assessments, were optimized taking into account the previous stages. Also the model defined by appling these active strategies were compared one to the other and with the base case concept. The focus of this research about ZEB is not to reach a specific ambition level but to highlight the impact of each change, step by step, on the CO_2 emissions taking advantage of the parametric design principles which allow to obtain a great quantities of models from few generative algorithms.

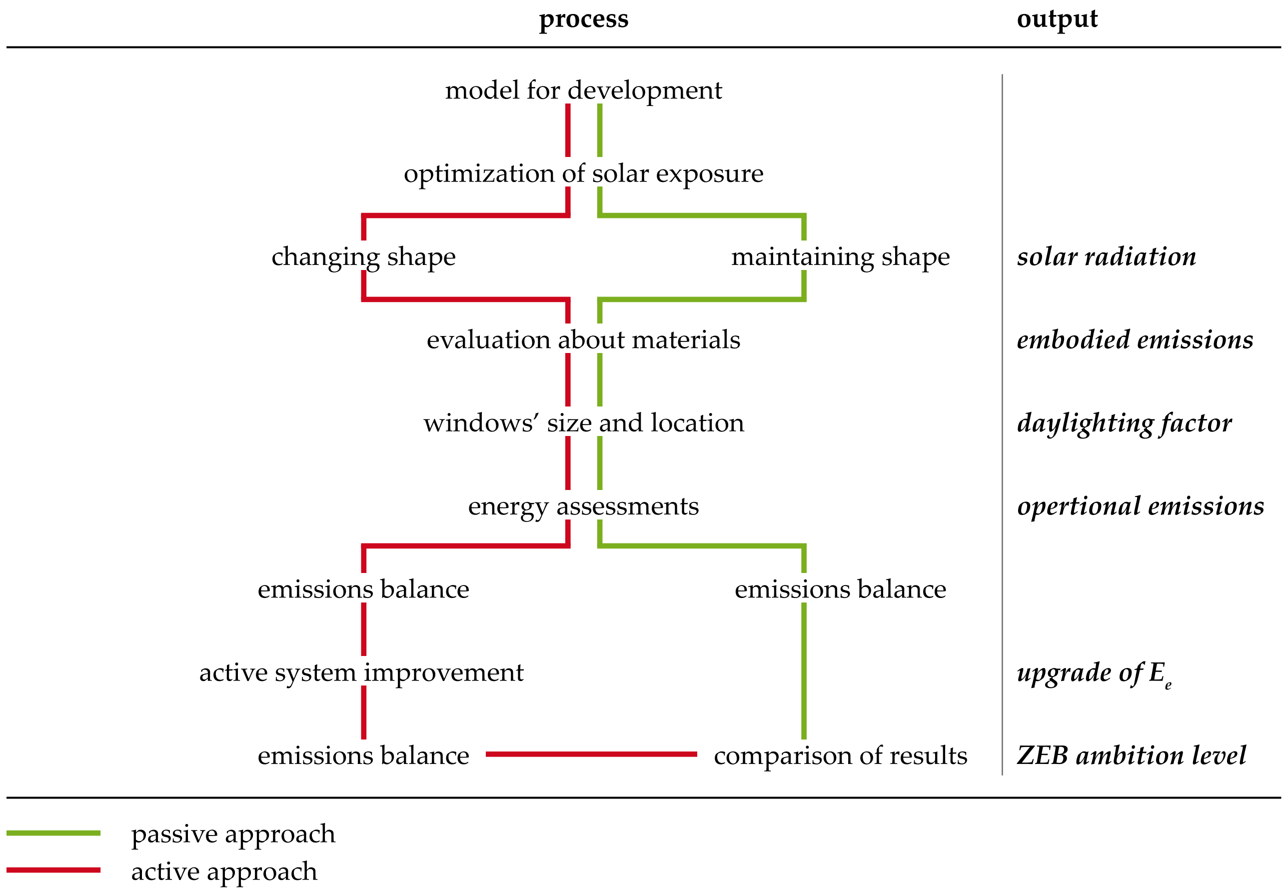


Figure 10 The diagram shows the path followed during the optimization process. The main differences between the two strategies are the approach to the shape's design and the exploitation of the active system.

analysis				optimization	concepts	model
Ee	Eo	DF	SR			
●	●	●	●	-		stage 0
			●	Galapagos (SR)		stage 1
●		●		manually (DF)		stage 2
●	●	●	●	Galapagos (DF) manually (LCA)		stage 3
●			●	Octopus (SR, LCA)		stage 4
●			●	Octopus (SR, LCA)		stage 5
●	●	●	●	manually (DF)		stage 6

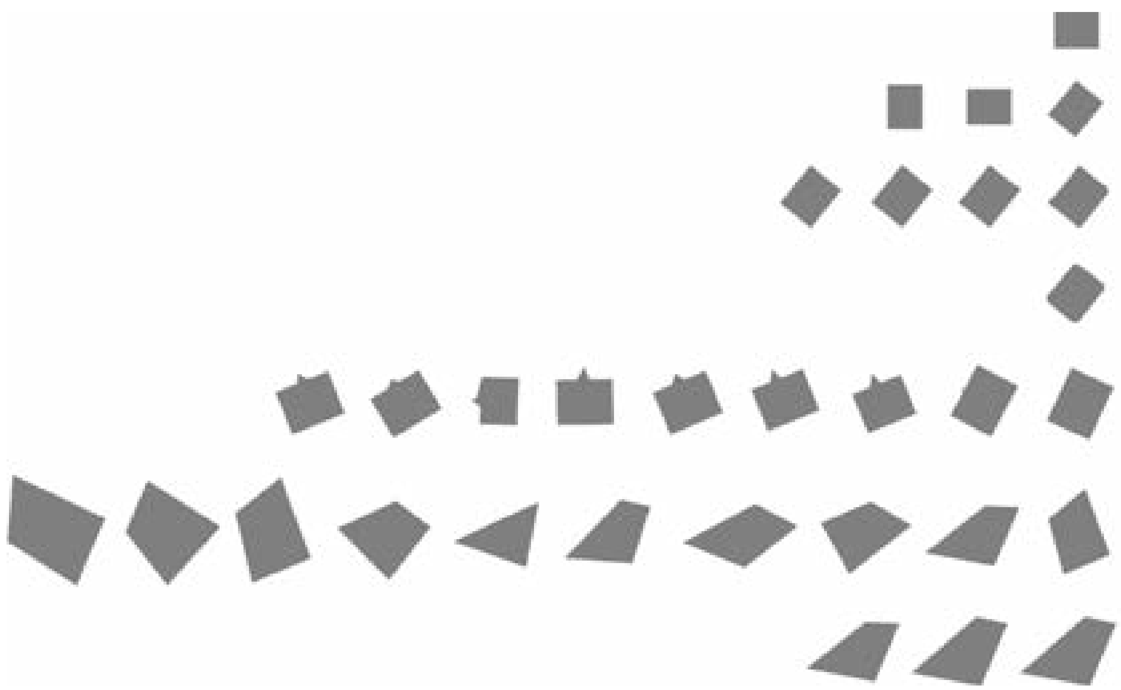


Table 8 The optimization process is composed by seven stages, from “stage 0” (initial box-shape model) to “stage 6” (final developed model). During each stage, at least one building’s feature was optimized in order to generate a more environmentally responsive construction. The scheme above reported the analyses developed (operational emissions, embodied emissions, solar radiation, daylighting) for each step as well as the optimized properties.

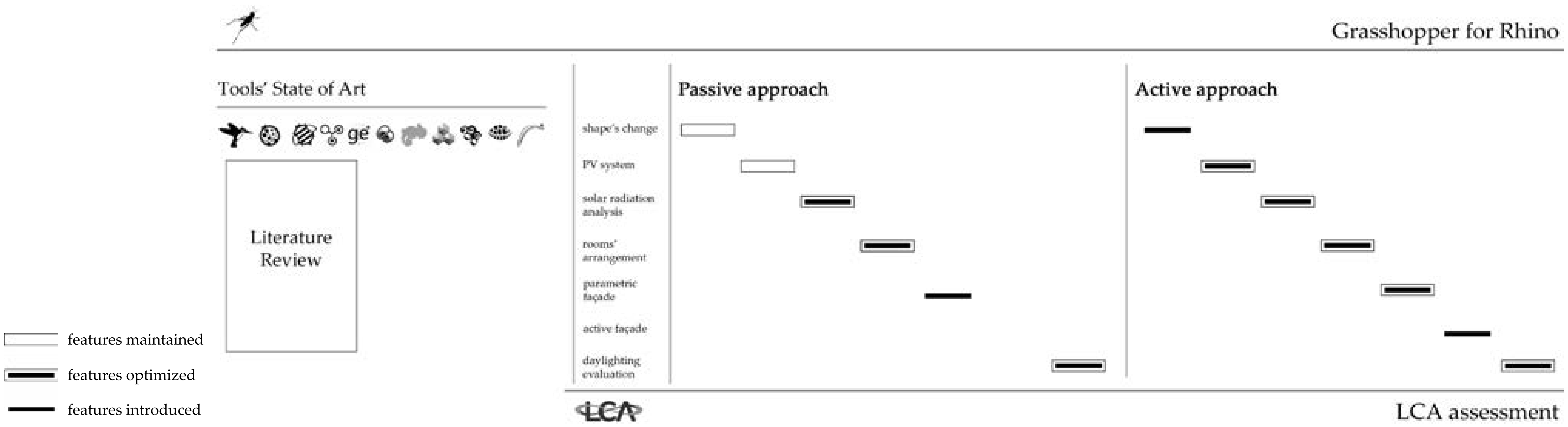


Figure 11 The table above shows the general workflow applied to the development of the base case model. After a first part where it was realized the literature review and the state of art of usable tools, the thesis was focused on the application of the parametric design principles to generate an environmentally responsive architecture. The approach to the building’s features such as the shape and the roooms’ arrangement are reported on the figure above.

3.2 TOOLS REVIEW

3.2.1 List of tools

Legend

gh.	grasshopper
rh.	rhinoceros
re.	revit
par.	parametric
opt.	optimization
env.	environmental analysis
ene.	energetic assessments
bim.	bim model

Archsim Energy Modeling [*gh. ene.*] is a plugin for Grasshopper that introduced for the first time EnergyPlus simulation engine on Rhinoceros environment. Archsim allows to create complex multi-zone energy models, simulate them and visualize results. It is typically used for rapid early design exploration in which building shape, window to wall ratios, façade and passive approaches are tested for calculating their impact on the building's energy performance. Simulation inputs are fully parametric and can be coupled with generative algorithms of Grasshopper.

Chamaleon [*gh. bim.*] is a plugin for both Grasshopper and Autodesk Revit with a focus on interoperability, simulations and efficient practice workflows. Its main advantage is the ability to transfer easily geometric data from Grasshopper to Autodesk Revit, and vice versa. Anyway, it doesn't permit the setting of families and other information about geometry.

Diva for Rhino [*gh.* or *rh. env.*] is a daylighting and energy plug-in for both Rhinoceros and Grasshopper which exploits the Radiance engine to calculate th Daylighting Factor (DF) and the Solar Radiation (SR). The version released for Rhino guarantees a better accessibility to the data and seems to be more reliable. It allows to carry out a series of evaluations about environmental performance for individual buildings or urban landscapes. It was employed during this master thesis to analyze all the configuration tested by evolutionary solvers to define a better environmentally responsive configuration.

Dynamo [*re. par.*] is a visual programming tool that aims at being accessible to both non-programmers and programmers. It gives users the ability to script using various textual programming languages. Like a Revit version of Grasshopper, it permits to work with parametric modeling in BIM environment. As Grasshopper and its tools, it allows to run several simulations and analyses such as structural or energetic.

Galapagos [*gh. opt.*] is a Grasshopper component, not a plug-in, which allows to integrate the Evolutionary Theory and parametric modeling on the Evolutionary Computing Theory. It permits to solve specific problems autonomously or optimize some building features by coupling with tools for structural or environmental analyses.

Geco [*gh. env.*] offers a direct link between Grasshopper models and Ecotect. It allows to quickly export complex geometries, evaluate the design in Ecotect and access the performances data. The results can be imported as feedback to Grasshopper. It could be a single process or a loop finalized to an optimization procedure.

Geometric Gym [*gh. bim.*] allows to export the model from Grasshopper to Autodesk Revit through an openBIM format (.ifc). It represents the most completed tool for linking these two platforms and a good solution because it *.ifc* can be used on other 3d software too. Nevertheless, it is quite far from the real-time connection that we were looking for.

Gerilla [*gh. ene.*] is a tool for Grasshopper that permits to develop building energy simulations integrating parametric modelling with EnergyPlus simulation engine. Anyway, Gerilla is an open source which is still in early development.

Grasshopper [*rh. par.*] is a graphical algorithm editor tightly integrated with Rhino's 3d modeling tools. Grasshopper requires no knowledge of programming or scripting and allows to explore shapes using generative algorithm.

Grevit [*gh. bim.*] allows to create BIM elements directly in Grasshopper and send them to Autodesk Revit. In this way, it is possible to assemble the element already in Grasshopper environment, so that their geometry and parameter can be update. Every element is characterized by an unique ID and it is sent to Revit platin order to be used on that platform.

Hummingbird [*gh. bim.*] is a set of Grasshopper components that allows the creation of Revit native geometry. It exports basic geometric properties and parameter data to *.csv* text files that is used for describing several aspects of the Revit BIM geometry. The data is imported in Revit platform using Whitefeet Modelbuilder, a tool included in Hummingbird package. In this way, it is possible to modify the model for the project duration. The last updates makes possible also a bi-directional workflow.

Honeybee [*gh. ene.*] connects Grasshopper to validated simulation engines such as EnergyPlus or Daysim for building energy and daylighting simulation.

Ladybug [*gh. env.*] represents with Honeybee a couple of open source environmental plugins for Grasshopper. They help designers to create an environmentally-conscious architectural design. It is possible to import and analyze standard weather data and draw diagrams like sun-path or radiation-rose. It allows to evaluate the solar radiation and the shadows' system.

Lyrebird [*gh. bim.*] is a tool for Grasshopper that composed by a component, LBOut, for sending information toward Autodesk Revit. Unfortunately, it is the first release and it still contain bugs and errors.

Octopus [*gh. opt.*] is a tool for applying evolutionary principles to parametric design and problem solving. Differently from Galapagos, it allows to optimize several goals at once. In other words, it can be set more than one fitness.

Tortuga [*gh. ene.*] evaluates the Life Cycle Analysis of the model in terms of GWP. The materials and systems for applying to the model's element are chosen among the ones proposed and updated from Okobau database. Tortuga can display calculated GWP values and colorize the geometry accordingly in order to compare quickly different design solutions. Unfortunately, the last release of the Okobau database (2015) is rejected by the component and it forces the users to employ the previous release (2013)

3.2 TOOLS' REVIEW

3.2.2 Introduction

In this section, it has been reported the tools' state of art introducing the groups of components which permit to develop analysis about carbon emissions, solar radiation and daylighting in a parametric environment as Grasshopper. Not all the components presented below have been employed during the development of this research. For example, even if it has been introduced Honeybee for energy assessments and for interfacing with Energy Plus engine, during the study it has been necessary to use a software like Design Builder in order to have a better overview of the results. In that case the parametric design principles have been sacrified for reaching a better managing of data.

3.2.3 Evolutionary computing

The tools such as Galapagos or Octopus allow to apply the main rules of Darwin Evolutionary Theory to the problem solving. Both of them work with genome and fitness, which are terms from the biological application of Darwinism. The first represents the values of all parameters (genes) which can be changed for adapting the consequent configuration to the new environment. On the other hand, the fitness is the parameter which we are trying to minimize or maximize, it represents the ability to adapt of the genome, so the ability to solve our problem. All the fitnesses are depicted on a Fitness Landscape, a *n+1* dimensional graph, where *n* is the number of genes on our model. The Landscape is characterized by some peaks which correspond with the higher Fitness values. The software doesn't know the Fitness Landscape, otherwise there is no need of finding the solution through generative algorithms. Galapagos, or Octopus, starts working creating a first population with random combinations of genes, selects the stronger and thrugh crossovers and mutations allows them to reproduce in order to find one of the peaks at least. That is the Natural Selection of Species semplified and applied to problem solving. Following that way, these tools are able to select some Fitnesses, which will not be probably the best gruop of solution because we don't know how many peaks are on the Fitness Landscape and where they are. In fact, the same problem could be solved following different paths or appling different strategies: through the Evolutionary Computing it is possible to find some of that approaches, some of the several organisms able to adapt to the environment. Anyway, sometimes we need to optimize more than only one parameter, which means that we are looking for an organism able to adapt to more than only one environment. The main difference between the two tools presented at the beginning is related to that: Galapagos is able to work with only one Fitness for each time, it means that once i have already optimized one Fitness, if I try to optimize another I will probably lose the better first configuration's genome. Otherwise, Octopus permits to optimize more than one Fitness contemporaneously so that there are no risk at all to lose anything. For instance, it could be possible using Galapagos for optimizing the total solar radiation incoming or for minimizing the volume. Instead, appling Octopus you could find the configuration with the highest total solar radiation caught and the lowest value of volume. Actually, as it is written above, it is not really correct refering to "lowest" or "highest" because both the tools explore the Fitness Landscape without knowing it, so they could find a local optimum, not necessarily the absolute one. The two tools are not interchangeable, or better Octopus can works as Galapagos while the opposite is not possible. By the way, we have used Galapagos when we tried to optimize only one Fitness because its interface seems easier to use than Octopus. Instead,

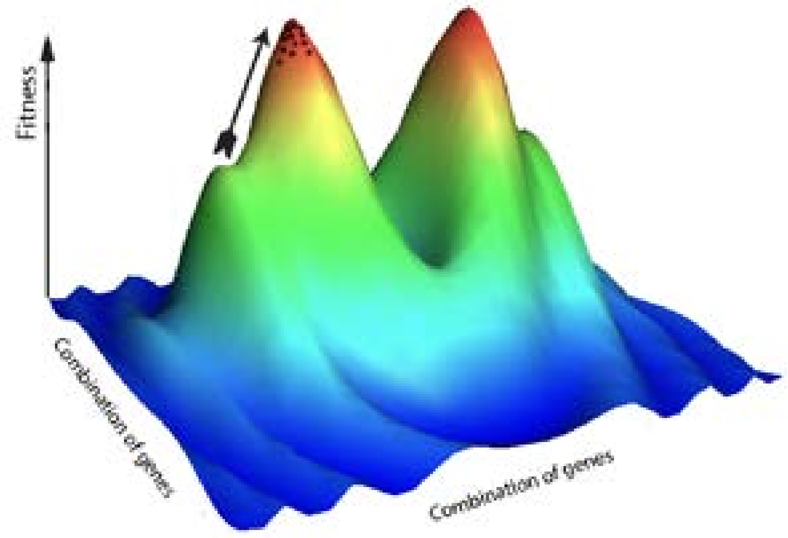


Figure 12 A combination of genes and their related fitnesses forms the Fitness Landscape. It is a *n+1* dimensional graph, where *n* is the number of genes on our model (in that example *n=2*). The selection pushes populations toward the peaks in order to find a local, or sometimes global, optimum.

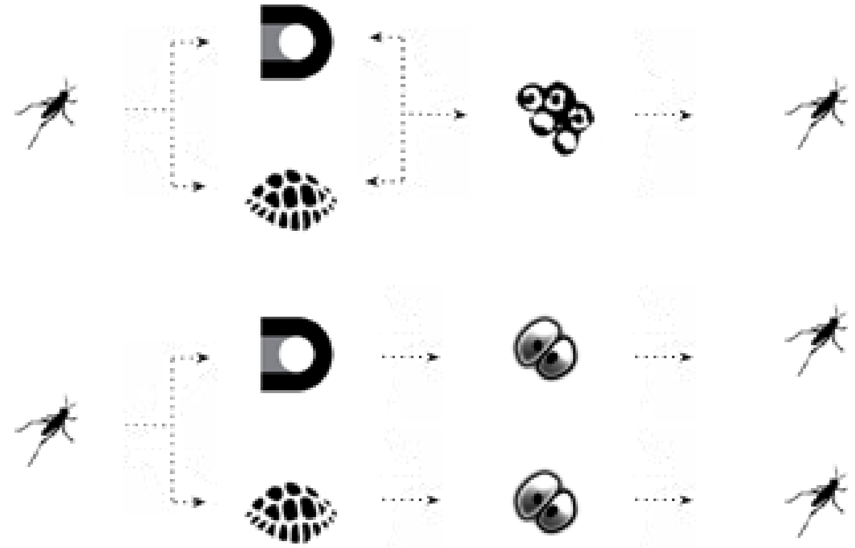


Figure 13 Optimization process. Appling Galapagos and others tools for analysis, it can be reached a different configuration for each analysis. Otherwise, Octopus permits to find the model which optimize both the analysis, in this case Diva and Tortuga.

when we had to work with more than one Fitness, we have used Octopus for appling evolutionary computing. unfortunately, Galapagos doesn't allow users to save the configurations examined as Octopus does. It is really useful such as the graph where all of them are depicted. Anyway, it is not possible to choose the type of process which has to be applied on Octopus like "maximization" or "minimization": the tool try to find both the extreme values. A good practice is to work with minimization with all the Fitnesses so that the better solutions will be the ones nearest to the origin of graph. In conclusion, the evolutionary algorithms could be applied for solving several problems such as the ones in which you have to choose among different way of using finite resources or the ones that request to find the optimal arrangement of some elements in porsuit of fixed requisit such as functional, aesthetic or structural. What it seems really common and easily accessible nowadays was not so widespread not more than half century ago: for instance, Frank Gehry was not able to optimize more than two Fitness at the same time with using the firsts software for optimization.

3.2.4 Environmental analysis

In order to plan efficient building, it is necessary to assess the environmental contribute, especially about solar radiation and daylighting. A good exploitation of the resources permits to reduce the building consumption minimizing its ecological footprint. The tools analysed on this paragraph let us know how a group of parameters could change some features, such as the total solar radiation caught. The main tool used on this work is Diva, developed for both Rhinoceros and Grasshopper. It simulates the sun contribute after the building location has been set from an .epw file. Appling Diva, a grid of test points is created on building surfaces and random sunrays hit them during the simulation. That randomness is the reason for the little differences among the results of several simulations run with same parameters. Diva for Grasshopper is easy to use, with an intuitive interface and allow to set the surfaces' material so that it can better evaluate the radiation reflected. Furthermore, the most recent tool release has been developed adding the possibility of analyzing the building thermal properties in order to know, for instance, the heat flow through the envelope. Although we have firstly employed Diva for our assessments, there is another tool probably better than this and we have used it for running again the simulation about solar radiation following a different approach. It is Lady Bug and since you install it, it is easy to understand its complexity. It is due to the more informations which can be managed by the tool, for instance it is possible to extract a lot of data from the weather file and draw a sunpath or other graphs about temperature variation through the year. The higher complexity is shown also by the great amount of inputs and outputs on Grasshopper button with a lot of parameters which can be set. Although there are a great quantities of parameters to be set, it is not possible to assign materials to the surfaces, as Diva does. By the way, the analysis engine is really faster than Diva and it is really usefull while we are appling an optimization process coupling it with Galapagos (or Octopus). While Diva and Lady Bug allow to run the environmental analysis directly on Grasshopper platform, Geco is a plug-in for exporting the geometry to Ecotect and making the assessments on a different platform. Although it works as well as the others, we have prefered using a plug-in which would not involve new softwares, unless it was not indispensable. In conclusion, it is worth wasting few hours on understanding Lady Bug's layout and principles considering the high potentiality of tool, especially if compared to Diva.

3.2.5 Energy analysis

In the last years, it has been developed a huge group of tools for introducing energy analysis on Grasshopper environment. They are able to show to users how a change of geometry, managed through parametric algorithm, could influence the building's energy performances. All the main tools work coupled with EnergyPlus engine; the first able to permit that connection has been Archsim Energy Modelling, a Grasshopper's application for performance and comfort assessments. It is usually employed for early design exploration, when some building features, such as shape or windows' position and dimension, are not definite and the planner wants to know the energy

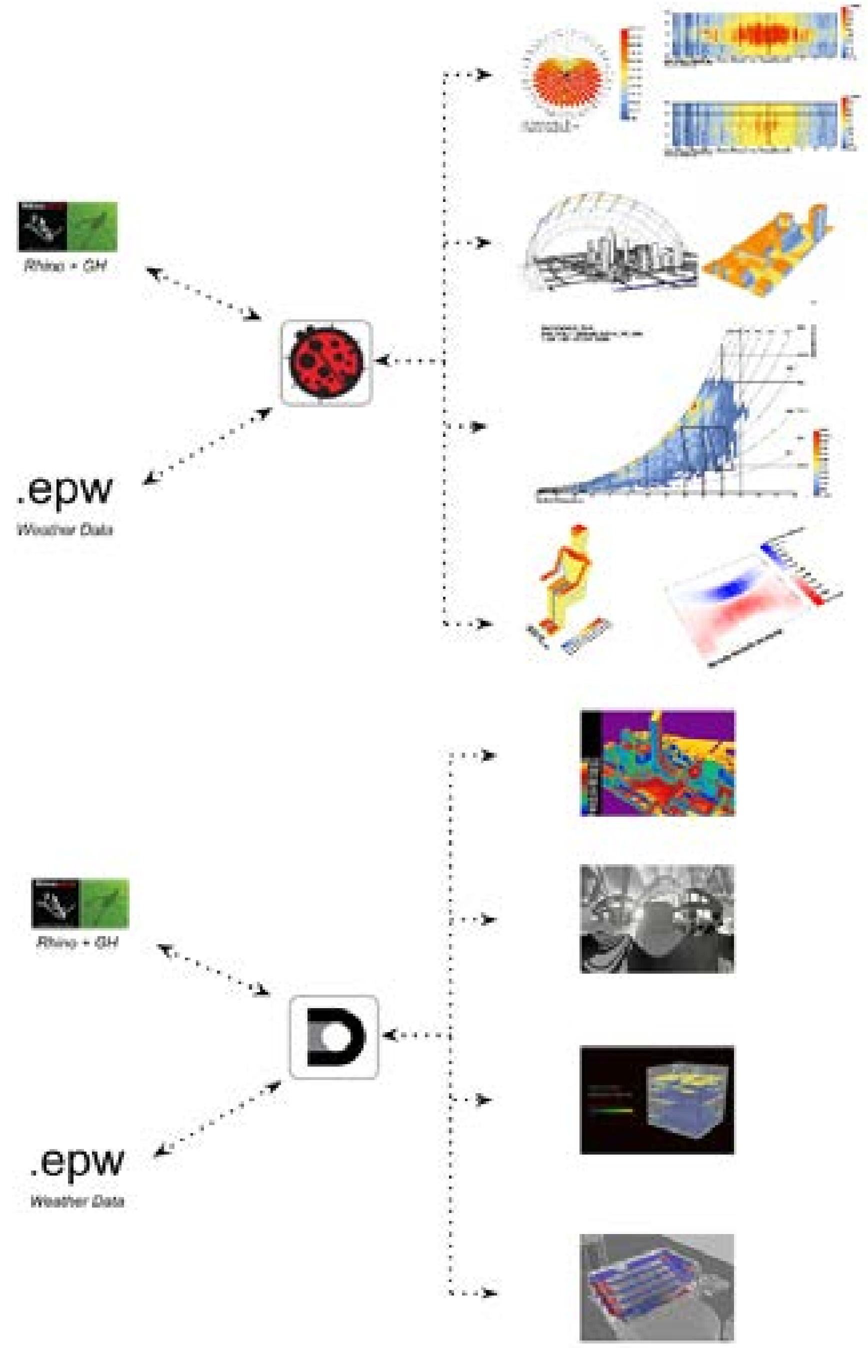


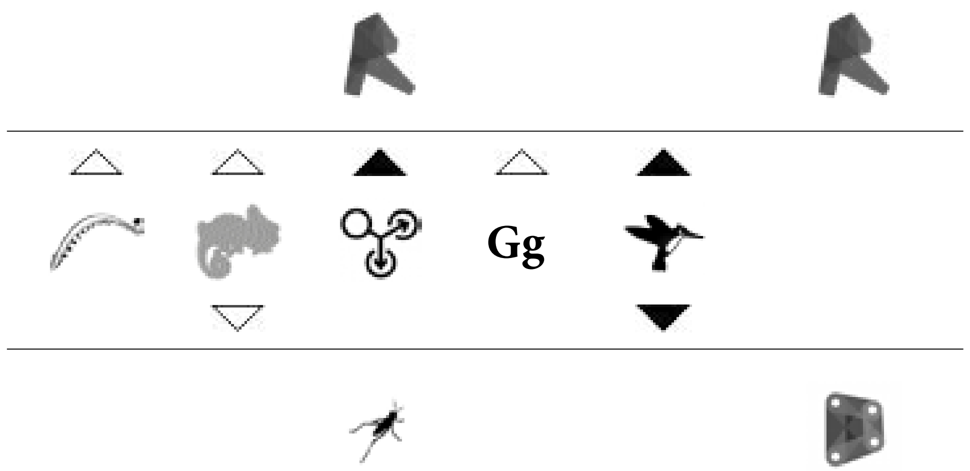
Figure 14 Diva and Lady Bug have similar applications and workflow too; anyway, they manage the weather file in different way. Lady Bug allows to examine more in depth than Diva with a more elaborate output.

impact of several configurations. As Archsim, also Gerilla, the most recent among the energy tools proposed on this paper, allows to divide the building in different zones and surfaces before running EnergyPlus simulation. Developed on early 1980s by the U.S. Department of Energy, EnergyPlus is an open source based on the two previous programmes BLAST and DOE-2. It guarantees high performances and reliability, allowing users to evaluate several assessment such as dynamic simulation for energy load and analysis about energy performance, hosts' comfort and daylighting. All those potentials have been increased by Honey Bee coupling EnergyPlus engine with Daysim, a specific tool for daylighting analysis. Probably, Honey Bee is the most interesting energy tool: it starts being released as a part of Lady Bug toolbar, but in few years its applications have been developed accurately. Like LB, it permits to easy manage .epw weather files for examining in depth some some context's features like temperature, solar radiation, wind or cluod density. HB permits to set not only the climate file, but also the layers which form the walls and other elements, thermal and solar properties of materials employed. A different approach to the energy analysis is introduced by Tortuga which allows to run easily LCA assessments and compare the relusts rapidly. It developes LCA analysis based on Okoban.dat database, a collection of data from Germany. All the materials which can be set are from that database. The simulation result is a geometry coloured on the basis of the element's impact. Surely Tortuga is not the best application for developing LCA evaluation, but at the moment is the only one exisiting for Grasshopper. A consequent advantage is that user can couple Tortuga with Galapagos or Octopus for minimizing the Global Warming Potential, for instance. Anyway, it is preferable using this in early design exploration for understanding how a parameter could influence the final GWP. Following that path, it is possible to explore several configurations and see the main differences; later, it could be run a more detailed LCA analysis for the selected models.

3.2.6 Link to BIM model

The growing complexity of building planning during the last half century makes necessary creating new and more complex representetion tecniques. The three dimensional graphs are not enough anymore, we need to add to the element's drawings informations about materials, thermal or structural properties, descriptions of systems which serve the house, etc. That gap has been filled by the introduction of BIM, Building Information Modelling, a virtual model where all the features and data about the building can be included. Therefore, both the BIM and the parametric modelling seem to represent the future of planning. Despite of it, it is not yet easy working with both, the BIM tools are different from the ones for parametric modelling and their interconnection is one of the contemporary challenges for architecture tools' programmers. It is highlighed by the great variety of tools which propose a virtual bridge between those softwares, each one with its qualities and lacks. Below, we try to evaluate the main tools avialable, looking for a real-time connection from Grasshopper to Revit. All the tools assessed are able to send a geometry from Grasshopper to Revit, but only someones, such as Chamaleon and Hummingbird, can do the opposite. Chamaleon is probably the easiest to use tool, but it is the one which works with less information to. In fact, it is the only which simply send to Revit the geometry without adding anything about families, for instance. Those informations could be added if you work with Hummingbird, but using that you have to work with a less direct connection. The geometry and the releted informations are exported through a .csv text file in which an ID code is assigned to every element. The .csv text file can be managed with the specific software Whitefeet Modelbuilder and everytime the geometry change the file is updated. The increasing of informations makes the workflow more complex and similar to Grevit approach. Grevit allows only to export geometry from Grasshopper creating a text file with a list of elements and their ID code. The tool nearest to reach the real-time connection, which we are looking for, is probably Lyrebird. It creates a virtual bridge with the implement LB Out which starts a dialogue between the two softwares without need of using third programmes for managing ID codes. Unfortunately, it is a really young tool (it exists only the first release) and it means that there are some bug or error or it still doesn't work very well. By the way, it seems a really good beginning and a promising tool. Waiting for a better version of Lyrebird, the more completed tool seems to be Geometry Gym in spite of it is really far from a real-time connection. Anyway, we estimate it as the best solution because it works with a openBIM format (.ifc) with no other programmes and allows to export the model towards other enviroments for several analysis too. An other approach to the problem has led to the creation of Dynamo, a plug-in for introducing parametric modelling directly in Revit environment. It works like Grasshopper for Rhino, but you need to write a new algorithm if you would work with that. We have considered using it, but we have prefered to continue working with a software as Grasshopper because we are more familiar with that and we need it for reaching other goals of this work. However, using Dynamo algorithm instead of Grasshopper could be a future development of this work. To sum up, there is not yet a tool which permits a real-time connection and the gap between Grasshopper and Revit it not filled, although a lot of tools exist and are working for it. We are quite sure that on the next years it will be possible linking parametric modelling to BIM environment; Dynamo and Lyrebird represent already two good proposals in this way.

Figure 15 Engines employed by the energy tools Archsim Energy Modelling, Gerilla, Honey Bee and Tortuga. Honey Bee has increased its potentials introducing specific tools for daylighting analysis such as Daysim and Radiance. Otherwise, Tortuga makes possible running LCA simulations in Grasshopper environment, even if the results are not really detailed.



△ no need of a third programme for managing exported information

▲ necessity of a third programme for managing exported information

Figure 16 How a parametric model could be linked to the BIM model. The triangles show the direction of the workfow and the necessity or not of a third programme for managing the exported information. In particular, the empty triangle means that you needn't another tool, the black triangle instead has the opposite meaning.

3.3 LCA CALCULATION AND ALGORITHM

3.3.1 State of the problem

The rapid growing of greenhouse gas (GHG) emissions and global atmospheric carbon dioxide (CO_2) concentrations during the last half century has been recognized as the main cause of the global warming. In the review about GHG emissions conducted by Heidari and Pearce [17] was pointed out liabilities such as the relevant role of renewable energies to mitigate the effect of climate change. The negative impact could influence the natural and socio-economic systems causing extra-ordinary events such as high temperatures and heat waves, crop failures, power outages, rising sea levels, erosion of shorelines and other eventualities which are summarized on Table 9. On the basis of IPCC Fifth Assessment Report [18], the 95% of those negative events are due to human activities. They are caused mainly by combustion of fossil fuels that represented the dominant cause of global warming from 1951 to 2010. In order to analyze the impact of the material productions as well as to regulate their emissions it was developed the life-cycle assessment (LCA). LCA is a method for evaluating the environmental impact of a product considering the raw materials employed and the productive processes by considering the entire life cycle, literally from *cradle* to *gave*. It is one of the advantages of using that method given that all the production phases are considered. It allows to know the ecological footprint of the models during the early stages of the design process as well as to find the most environmentally friendly configuration that permits to maintain the satisfaction level reducing materials' impact and quantity.

3.3.2 Life Cycle Assessment

Life Cycle Assessment is a method that evaluates the environmental impact of manufacturing products. The investigation is organized in five different phases such as (i) supply of raw materials, (ii) production, (iii) possible packaging and trasport in situ, (iv) operational stage, maintenance and repair, (v) disposal or reuse. It permits to compare different solutions by calculating their impacts. The publish International Standard ISO 14040:2006 [19], developed by International Organization for Standardization, describes the principles of the LCA and the Life Cycle Inventory (ISO 14041). However, it does not contain any specific method or detailed technique. In accordance with ISO 14040-14044, it is possible to consider four main phases: (i) *goals and definition phase*; (ii) *Life Cycle Inventory (LCI) analysis phase*; (iii) *Life Cycle Impact Assessment phase (LCIA)* defined on ISO 14042 and (iv) *Life Cycle Interpretation* introduced with ISO 14043. The process is iterative given that quality and completeness of information and its reliability is constantly tested. The first stage provides the main information about the assessment such as the system boundaries and the functional unit. In fact, the results of LCA change significantly depending on the analyses' accuracy. For example, the evaluation of the embodied emissions of a product changes significantly if the system boundaries included or not the transportation. Similarly, it is not correct to compare emissions calculated for different functional unit such as BRA and BYA. In the second step, the LCI assessment phase, it must be defined all the inputs and outputs data necessary for the calculation such as employed energy or emissions values. It consists on a detailed definition of all the flows in and out of the product system, including raw resources or materials, energy by type, water and emissions to air, water and land by specific substance. This process is articulate and may involve many unit processes in a supply chain in addition to hundreds tracked substances. LCIA represents the third phase. During

consequence of climatic change	references
higher temperatures and heat waves	[22-24]
crop failures and global hunger	[25,26] [27-30]
power outages	[31,32]
rising sealevels and low-lying coastal areas to submerge gradually	[33,34]
erosion of shorelines	[35,36]
increased risk of flooding	[37]
salt water intrusion	[35,38]
strong storms on coastal environments	[39-42]
droughts	[43]
fire	[41,44]

Table 9 List of negative consequences of climatic change and their references.

that phase, the LCI is classified accordingly to the environmental impact. The Athena Sustainable Materials Institute [20] defines it as the "what does it mean step" because it is the specific stage for knowing the global warming impact from the employment of resources previously defined as a quantity during the LCI. For example, manufacturing a product may consume a defined volume of natural gas as shown by the data on the inventory; in the LCIA phase, the global warming impact from combustion of that fuel is calculated. There are methods to categorize and characterize the life cycle impact of the flows to and from the environment: all of them must take into account the variables defined at the beginning such as the system boundaries and the functional unit. The last part is the interpretation of the previous evaluation, the conclusion of the study and the definition of the reached impact level. The stages, which compose this procedure, should not be confused with *Life Cycle Costing*, LCC. It is a life cycle approach that looks at the direct monetary costs involved with a product or service, without takiing into account the environmental impact. As the aforementioned procedure the approach to the buildings' LCA assessments considers the data about materials and other component including also the energy quantities for the operational stage. There are many international methods, which can be applied for conducting the evaluations [21]:

- *Dutch method*, Eco-indicator 99, three impact categories for the evaluation like human health, ecosystem quality and resources;
- *Swedish method*, Environmental Priority Strategies in Product Development (EPS 2000), the impact categories flow into other four categories of environmental damage such as human health, ecosystem production capacity, abiotic stock resources, biodiversity;
- *Danish method*, Environmental Design of Industrial Product (EDIP), as the first it considers three categorie as environmental impact, resources consumption, impact on the working;
- *Swiss method*, IMPACT 2002 +, the four categories for estimating the impact take into account human health, ecosystem quality, climate change, resources.

The International Organization for Standardization issued a specific regulations about the method to evaluate buildings' construction through ISO 21930:2007 in which the principles and requirements for building product are explained. The caption "*type III environmental declarations*" is used on the regulations instead of *Environmental Product Declarations* (EPD). They are organized in accordance with ISO 14025. An EPD is an independent verified and registered document that communicates information about the life-cycle environmental impact of products. Having an EPD for a product does not imply that the declared product is environmentally superior to alternatives. It is a transparent declaration of the life-cycle environmental impact. Those information are collected and included on SimaPro's database that represents the commonest and easiest way for evaluating LCA. SimaPro allows users to access to several databases like EcoInvent, ETH, BUWAL250, Industry Data, IDEMAT 2001 and LCA Food DK. The Ökbau german database, which is the one employed by Tortuga, a component of GH for evaluating the Global Warming Potential (GWP), is not included among the possibilities guaranteed by Simapro. In this master thesis as well as other works developed by ZEB Centre in Trondheim they were used data from EcoInvent, a database with more than 4000 inventory data released by EcoInvent Centre. In several countries, there are not any specific data about local materials or local techniques, so they usually apply international values collected in Ecoinvent. The results seem to be not very accurate and they must be considered just as an empirical evaluation: this represents the main actual limit of LCA. For this reason the presented analysis on the ZEB Project report 21- 2015 [45], considers emissions' data from Norwegian EPDs instead of generic data from EcoInvent when it was possible. In addition, several researches developed within the ZEB Centre [45], investigate the influence of CO_{2eq} factor for electricity in the operational stage for the emissions' balance. The conversion from kWh to $kgCO_{2eq}$ is influenced by the Country process for producing electricity and its emissions. Thus, the same energy demand could have a different impact on the emissions in atmosphere depending on its energy network. In conclusion, by modifying the value of this factor, the results as well as the achievement of ZEB-OM level turn out to be modified because the E_o changes.

3.3.3 Functional Unit

type	abbreviation
gross floor area	BTA
heated floor space	BRA
net floor area	NTA
built up area	BYA

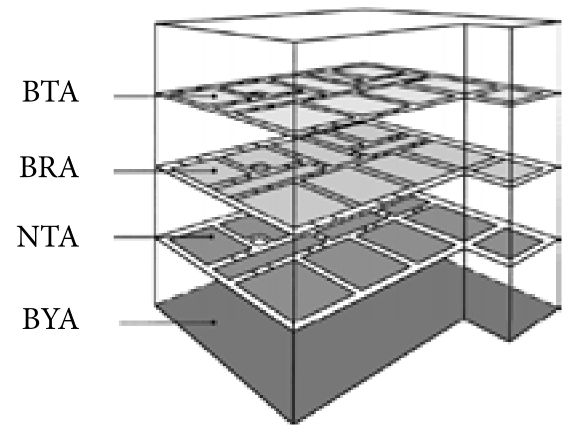


Figure 17 Area of the building in accordance with the Norsk Standard of 2012.

system boundary *EN 15804:2012*				
A1 - A3 Product stage	**A4 - A5** Construction process stage	**B1 - B7** Use stage	**C1 - C4** End of life stage	**D1- D4** Benefits and loads beyond the system boundary
A1 Raw material supply **A2** Transport to manufacturer **A3** Manufacturing	**A4** Transport to building site **A5** Installation into building	**B1** Use **B2** Maintenance **B3** Repair **B4** Replacement **B5** Refurbishment **B6** Operational energy use **B7** Operational water use	**C1** Deconstruction / demolition **C2** Transport to end of life **C3** Waste processing **C4** Disposal	**D1** Reuse **D2** Recovery **D3** Recycling **D4** Exported energy / potential

Table 10 System boundary (NS 15804 Sustainability of construction works, Environmental product declarations, core rules for the product category of construction products, 2013)

The definition of a functional unit is fundamental for LCA because it permits to compare different models such as surface and lifetime. Several methods can be identified for calculating buildings' area on the Norwegian Standard 3940:2012 (NS3940:2012) as shown on the Figure 17. The commonest building areas are:
- Gross area includes the external walls and all the internal walls and the floors (BTA);
- Heated floor area, with external walls not included (BRA);
- Area with any walls, internal or external, included (NTA);
- Building footprint (BYA).

The chosen functional unit is 1 m^2 of heated floor area (BRA) and the life time of the building has been set at 60 years as well as on the life cycle calculation of ZEB Centre. Thus, the functional unit is BRA per 60 years' service lifetime.

3.3.4 System Boundaries

In this section, they are established the unit processes considered on the evaluation of the emissions in atmosphere. The boundaries are defined during the scope phase and it represents a subjective choice depending on the accuracy of the calculation. There are five different steps and each of them evaluates a specific aspect of the product's life cycle. The different phases and the categories are summarized in Table 10. For the estimated calculation during this master thesis, as was done in the other evaluations reported on the ZEB Project report 21- 2015 [45], the following parts of the life cycle have been considered: raw materials supply, transport to manufacturer and manufacturing (product stage, A1-A3); replacement and operational energy use (use stage, B4, B6).

3.3.5 LCA algorithm

The platform chosen for calculating the LCA is Grasshopper for Rhino, a plug-in that allows to create and easy manage complex algorithms. The approach to geometry and data is fully parametric: there are several numeric input parameters, which can be changed for modifying the output. In that regards, the model was developed as a prototype of a two-storey house with a low value of emission evaluated as $kgCO_{2eq}$. Thus, it was chosen the E_e for comparing the results and estimating the impact of each parameter. As it has been already presented in the chapter #, some tools allow users to evaluate the LCA such as *Honeybee* and *Tortuga*. All of them permit to set the materials only from an existing database without possibility of managing their property. *Tortuga* works with the German database Oekobau, while *Honeybee* uses the material library of Energy Plus. Kokkos's research [47] about the *Design for deconstruction*, brought him to the creation of a new Grasshopper's component for estimating costs and environmental impact (LCC, LCA), through the employment of script components like Visual Basic. The result is a group of components for LCI, LCIA and financial assessments applied to steel frame. Nevertheless, for reaching the goals of this thesis, the calculations, which are mainly mathematical operations, were managed through the Evaluate component of Grasshopper. The interface of the developed algorithm was not as good as the one of other tools, but it is more similar to Microsoft Excel's layout and it allows to manage several properties about materials. The LCA algorithm must be coupled with another which describes the building geometry in order to assign to each volume the materials' properties. Each layer is characterized by geometric and physic properties such as thickness, lifetime, density and $kgCO_{2eq}/kg$. They can be changed as the user prefers. The output values for each material are the volume and the $kgCO_{2eq}$ which are summarized on a pie chart for highlighting the different impacts. The interface is divided in four parts and each one has its specific function: three of them are for input, the fourth is for output. The first group allows to manage the building's geometry (i.e. number of floors, length, width, orientation, room's height, percentage of indoor wall's area, etc.), the geometric layer's properties (i.e. thickness, volume, etc.) and the physic material's properties (i.e. lifetime, density, $kgCO_{2eq}/kg$, etc.). All these data are managed by the Evaluate component that starts summing the volume of different layers made by same material. Unfortunately, this process needs to be set manually, the component

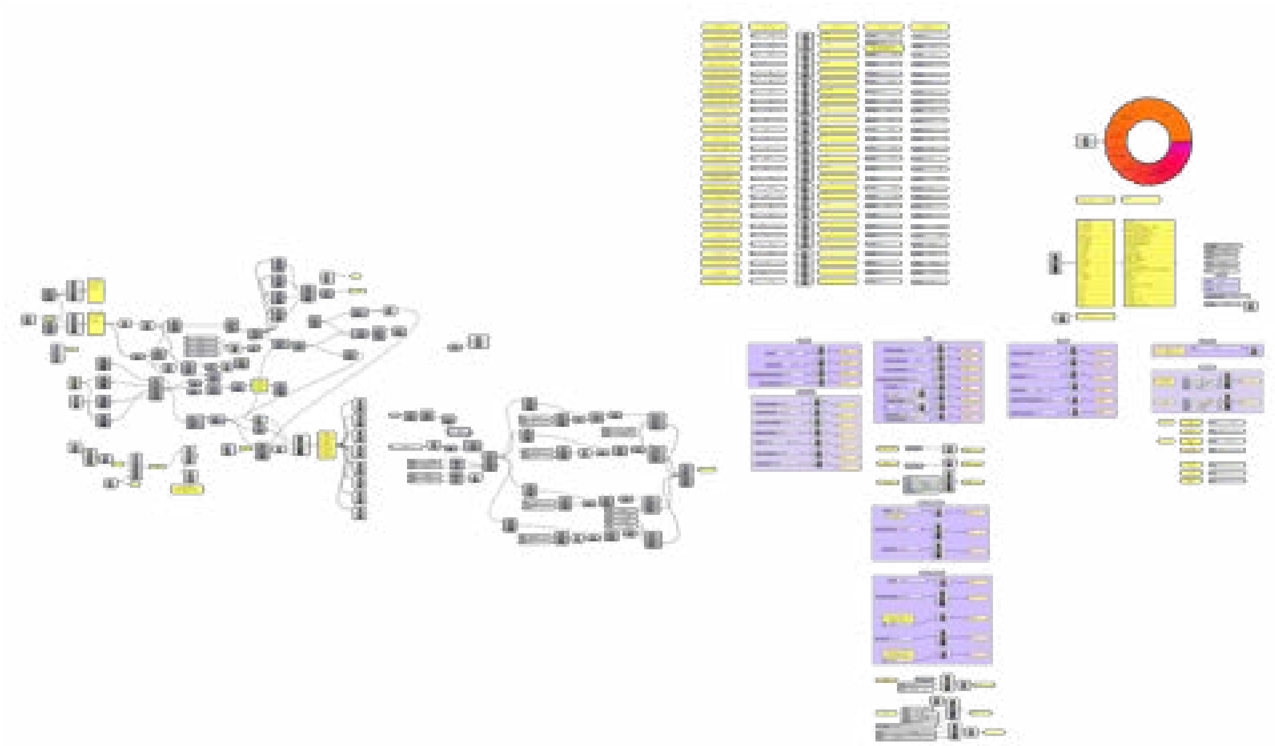


Figure 18 The algorithm works coupling a part, on the left, which describes building geometry and manages the Rhino's preview, with another one, on the right, specific for LCA assessments. The second is divided in four sections for better controlling the model's input and easily reading the output results.

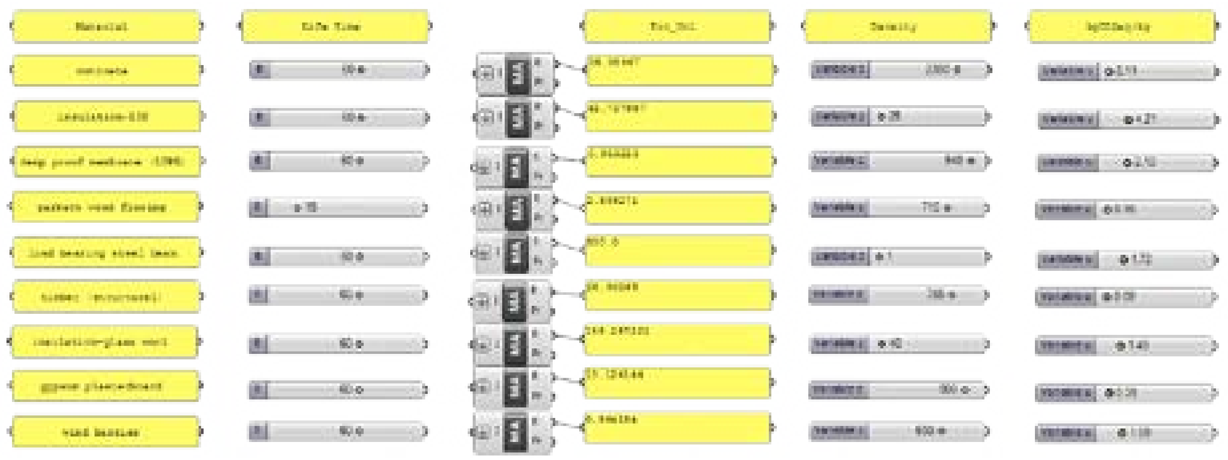


Figure 19 The table above allows users to manage the input phisic parameters and shows the total volume for each material. Alle the data converge on the Evaluete component for estimating building's emissions.

is not able to find autonomously the similar layers. It is a long process, but it permits to have a complete control of data during the entire path. The following step is the LCA calculation: the Evaluate component divides the building's lifetime by the material's lifetime and multiplies the result by the values of volume, density and $kgCO_{2eq}/kg$. The calculation is repeated for all the materials and all the results are summed and represented on the pie chart. An example of how the algorithm works, is described below. It was modelled a two-storey house with an emission value near to 80 000 $kgCO_{2eq}$: it represents the base case. The house's geometry is generated by a GH algorithm by combining the components for evaluating CO_2 emissions. It is possible to modify the final configuration by changing some input parameters. The models were generated and analyzed in order to be compared to the base case. The first model has the same BRA but more levels, while the other maintains two storey increasing their area. The amount of $kgCO_{2eq}$ for each employed material is summarized on the graph shown on Figure 19. It represents a good way to consider and compare the emission caused by the used materials. A similar path was followed for analyzing the models developed during the whole optimization process.

3.3.6 Operational emissions

The evaluation of the emission balance takes into account the energy consumption during the operational stage. The operational emissions (E_o) are defined by Ibn-Mohammed et al. [48] as the emissions which encompasses all the activities related to the building's utilization, over its life span. Operational energy is the energy required for guaranteeing comfort conditions and daily maintenance of the buildings by operating processes such as heating, cooling, lighting and appliances. The consumption depends on the occupants, differently from the embodied emissions which are not related to the occupancy. For evaluating the E_o it is necessary to assess the building energy demand that was already calculated for base case model. Nevertheless, the ZEB pilot project of two-storey house was modeled in Design Builder (DB), a software that permits to exploit the Energy Plus engine. It was employed a tool that is not included in GH but it is particularly easy to manage and able to guarantee a huge variety of outputs. The model was already planned as an all-electric concept and DB permitted to have an idea of its energy demand by dividing it into two parts: thermal heating demand and electric-specific demand. The original systems included on the building are based on the state of art of the techniques used such as solar thermal collector, PV , heat pump air to air, fans and pumps. During the optimization process, others alternatives energy sources were taken into account such as the BIPV and the algae panel. The main systems' organization was maintained as much as possible. Otherwise, the devices for the energy production and their efficiency due to the sun exposure were modified. The production of the solar thermal collectors was calculated by DB, while the evaluation of PV, BIPV and AP production was calculated considering the SR caught and their efficiency.

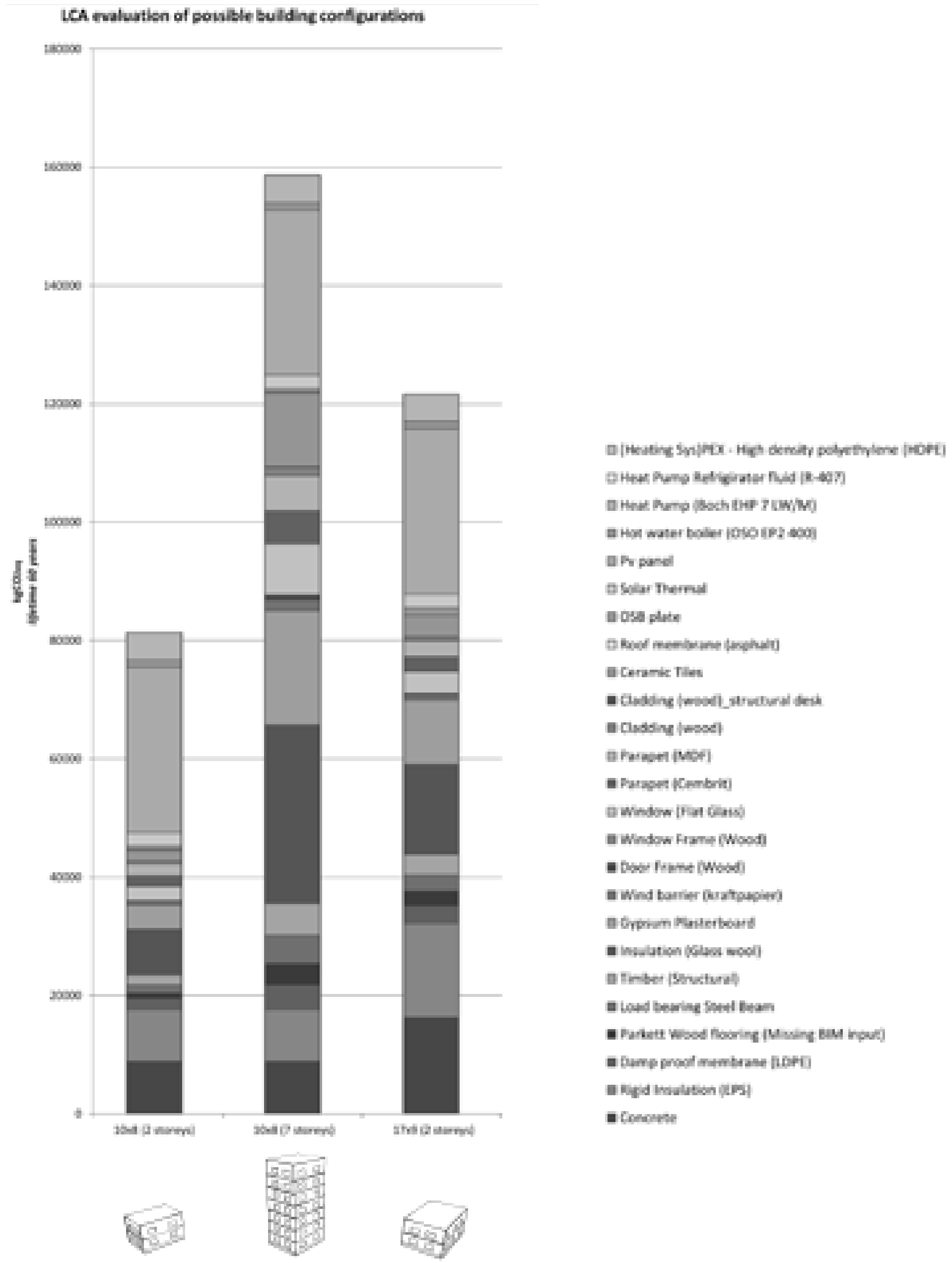


Figure 19 The graph shows the variations of embodied emissionsfor employed materials depending on the building's geometry. It is generate by a specific algorithm in Grasshopper environment.

3.4 ZEB PILOT MODEL

3.4.1 Stage 0: base case

The ZEB pilot project of a single family house, which is situated in Oslo, is a two storey dwelling with slab on ground. The box shape has a rectangular footprint, which is approximately 10.0 by 8.0 meters with the most extended façades facing South and North. The building contains four bedrooms and two bathrooms, which are arranged on two levels of 80 m^2. Thus, the total heated floor's extension (BRA) is 160 m^2. The door and windows' area is 36 m^2 and it covers the 35.0% of the façades. Moreover, the evaluated ratio windows/door to floor is 22.5%. Those features were maintained constant on the successive report released on 2015.

3.4.1.1 Thermal specification of the building envelope

Each material that composes the envelope is characterized by a high level of thermal performance. In Table 11 the transmittances for the parts of the building (i.e. external walls, external roof, slab on ground, etc.) are reported. The external wall is composed by a load baring timber frame coupled with an insulating layer 350 mm thick made by mineralwool. The outer wall, which is shown in Figure 20, achieves a U value of 0.12 W/m^2K. Differently, on the roof it was employed a thicker insulating layer (400 mm) that is supported by wooden load bearing truss beams. The main layers, which composes the ground floor's construction, are concrete (100 mm) and insulation (500 mm). Taking into account the thermal resistance in the ground the total value of transmittance is U= 0.06 W/m^2K. The windows are composed by three panels and an insulated frame; they achieve a U-value of 0.65 W/m^2K. The best practice principles were applied in order to minimize the thermal bridge, the windows should be positioned on the middle of the wall and the insulation is placed outside of the load bearing stracture. The Norwegian standards for passive house, NS 3700 contains the requirements necessary for the heat loss due to thermal bridges. Nevertheless, the base case was a concept and for now the thermal bridge heat loss budget is only indicative. However, it was respected a minimum requirement for the total heat loss number, 0.55 W/m^2K.

3.4.1.2 Ventilation system

The heating, ventilation and air conditioning (HVAC) system reaches a very high level of energy performance; the specification for the installation of ventilation and heating system are in Table 12. The air handling unit is located at the first floor in a storage room, instead an exhaust grill and air intake are placed on the northern façade. Furthermore, the air handling unit (AHU) is composed by a high efficiency rotary wheel exchanger. Its temperature efficiency is 85% and it permits to skip the conventional electric heating coil. The horizontal ductings are located in the load bearing wooden structure used for the roof and the floor partition. The forced ventilation extracts in the bathroom or in the kitchen, and it is compensated with supply air flow rate. The more specific data about air flow is contained into Table 13. When the house is unoccupied, the airflow rate is reduced. The standby mode is controlled and set the switch in the entrance.

3.4.1.3 Heating system

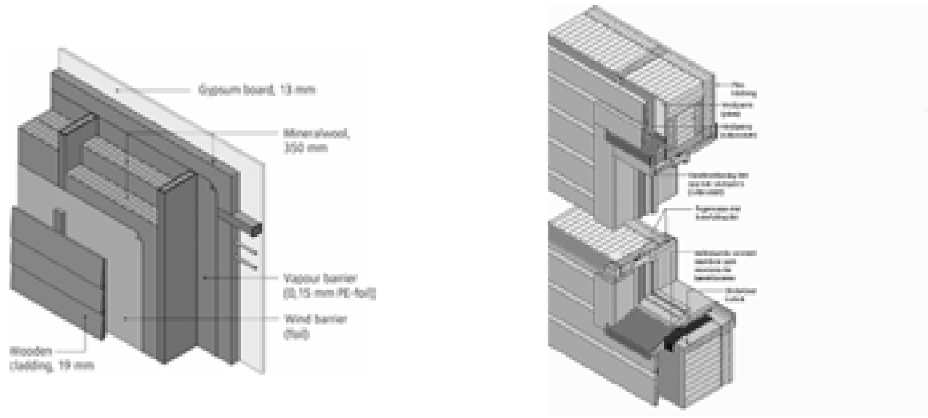


Figure 20 Principle sections of the external wall, opaque or glazed. The last shows the optimal position of a window regarding thermal performance (ZEB Project report 21 – 2015).

		values	*solution*
outer wall	W/m^2K	0.12	timbered wall with 350 mm insulation
roof	W/m^2K	0.10	compact roof with approximately 450 mm insulation
slab on ground	W/m^2K	0.07 (0.06)	floor construction with 500 mm insulation, the value in brackets considers the thermal resistence of the ground
windows	W/m^2K	0.65	three layer low energy windows, with insulated frame
doors	W/m^2K	0.65	well insulated doors
normalized thermal bridge	W/m^2K	0.03	detailed thermal bridge design
air tightness	n_{50}	≥ 0.30	detailed design of a continuous vapor and wind barrier

Table 11 Specification for the building's envelope (ZEB Project report 21 – 2015).

	values	*solution*
heat recovery	η = 85.0 %	rotary wheel heat exchanger
specific fan power	SFP = 1.0 $kW/(m^3/s)$	low pressure AHU and low pressure ducting system
installed cooling capacity	Q''_{cool} = 0 W/m^2	no cooling
installed heating capacity	Q''_{heat} = 18 W/m^2	installed capacity for hydronic floor heating and radiators

Table 12 Specification for the HVAC installation (ZEB Project report 21 – 2015).

The heating system is hydronic and it is characterized by two different type of terminals. A heated floor was used in the bathroom and in the entrance. Otherwise, the other rooms' heating demand is covered by two central radiators, one for each floor. The radiators are placed on the centre becausethe employment of insulated walls and triple glazed surfaces for windows permits to have a good insulating envelope. The arrangement of the terminals is shown in Figure 21. Moreover, the heating system is regulated by a pump that controls the variable flow. The maximum flow was calculated as:

$$M = 1\,000 \cdot Q/(\Delta T \cdot Cp \cdot \rho) = 1\,000 \cdot 18 \cdot 160 \,/\, (10 \cdot 4\,180 \cdot 988) = 0.07\ l/s$$

Q: Design heat load of 18 W/m² (2.9 kW)
ΔT: Temperature difference inlet and return in the hydronic system (45/35 °C inlet/return)
C : Heat capacity water, 4 180 J/kg K
ρ: Density water kg/m³, 988 kg/m³

In accordance with NS3031, a default specific pump power factor (SPP) for a constant volume system heating system is SPP = 0.5 kW/(l/s). The operational hours of heating is close to 2600 hours for years as verified with SIMIEN simulations. The final calculations of the pump energy is E = 54.0 kWh/m² year and this value represents a very small energy demand for the pump operational phase.

3.4.1.4 Lighting and appliances
The operational hours and type of lighting were estimated for each room. The average power demand and heat load for 16.0 hours of operation is E_{light} = 3 296.0/16.0 = 206.0 W or E''_{light} = 206.0/160.0 = 1.3 W/m², in accordance with NS3031. In conclusion, the total energy demand for lighting during a year is 7.6 kWh/m². There are two types of lighting appliances: LED spotlights and the LED lighting fixtures. The first group is installed on living room, kitchen, bathroom and staircase. The second group is placed on bedrooms and storages. This combinations results very efficient thanks to the double control of lighting system. It is possible to control it by the presence and by a standby switcher located in the entrance and "night switcher" in the main bedroom.

3.4.1.5 Appliances
Using appliances with high energy efficiency, it is possible to reduce the standard value used in NS3031 by approximately the 14.0 %. The specific energy demand of the ZEB pilot project for a single family house for appliances is: 2388.0/160.0 = 14.9 kWh/m² year.

3.4.1.6 Domestic hot water
The energy demand for domestic hot water (DHW) was estimated considering the NS3031. It is 30.0 kWh/m² year. The application of a grey water heat exchanger permits to improve the system. It should have an efficiency of approximately 40.0 %, with a nominal efficiency of 30.0 %. The grey water from showers, washing machine and dishwasher constitutes the 75.0 % of hot grey water. However, there are heat losses in the greywater pipes. Reducing those the demand should be reduced from 30.0 to 24.0 kWh/m² year.

3.4.1.7 Energy supply system: solar collector system

The energy supply is covered by all electric solution, which couples the solar collector with the PV system on the roof in order to satisty both the heat energy demand and the electric demand.
During the summer the vacuum tube solar collectors placed on the vertical South façade covered almost of the heat energy demand. The data from APRICUS model were utilized, considering the efficiency of 69.0 %. The total solar production was evaluated with the software PolySun. The storage capacity for this model of vacuum collectors is 600 litres. The 41.0 % of the total demand is sati-

room	*supply air*	*extract air*	*comment*
bedroom 1	26.0 m³/h	0.0 m³/h	for one person
bedroom 2	26.0 m³/h	0.0 m³/h	for one person
bedroom 3	26.0 m³/h	0.0 m³/h	for one person
bedroom 4	52.0 m³/h	0.0 m³/h	for two person
living room 1st floor	30.0 m³/h	0.0 m³/h	also overflow supply from bedrooms (78 m³/h)
living room/kitchen 2nd floor	32.0 m³/h	72.0 m³/h	also overflow supply from bedroom 4 (52 m³/h)
bathroom 1st floor	0.0 m³/h	60.0 m³/h	overflow through door opening
bathroom 2nd floor	0.0 m³/h	60.0 m³/h	overflow through door opening
total	192.0 m³/h	192.0 m³/h	gives: 1.2 m³/h m²

Table 13 Air flow rates in different rooms during normal operation (ZEB Project report 21 – 2015).

Figure 21 Hydronic heating system for the first and the second floors (ZEB Project report 21 – 2015).

room	*installed Wattage*	*estimated operation*	*Watt hours per day*	*comments*
bedroom 1	20.0 W	10.0 h/day	200.0 Wh	LED lighting fixtures
bedroom 2	20.0 W	10.0 h/day	200.0 Wh	LED lighting fixtures
bedroom 3	20.0 W	10.0 h/day	200.0 Wh	LED lighting fixtures
bedroom 4	20.0 W	10.0 h/day	200.0 Wh	LED lighting fixtures
storage 1st floor	12.0 W	10.0 h/day	24.0 Wh	LED lighting fixtures
storage 2nd floor	12.0 W	2.0 h/day	24.0 Wh	LED lighting fixtures
living room 1st floor	36.0 W	2.0 h/day	432.0 Wh	LED spotlight, 12 x 3 Watt
bathroom 1st floor	18.0 W	24.0 h/day	432.0 Wh	LED spotlight, 6 x 3 Watt
bathroom 2nd floor	18.0 W	24.0 h/day	432.0 Wh	LED spotlight, 6 x 3 Watt
living room 2nd floor	36.0 W	12.0 h/day	432.0 Wh	LED spotlight, 12 x 3 Watt
kitchen	36.0 W	12.0 h/day	432.0 Wh	LED spotlight, 12 x 3 Watt
staircase	12.0 W	24.0 h/day	288.0 Wh	LED spotlight, 4 x 3 Watt
total	260.0 W		3296.0 Wh	

Table 14 Installed lighting level (Watt) and estimated hours of operation for different rooms in the SFH. (ZEB Project report 21 – 2015).

sfyed with a collectors' area of 8.3 m^2 and the total solar thermal production is 3 374 kWh/year. The diagram reported in Figure 22 shows how heat pump and solar collectors system cover the demand month by month. The vertical positions of the collectors guarantees also a contribution during the winter, when the sun is along the horizon.

3.4.1.8 Heat pump system

The heat pump system is an air-to-water heat pump and exploits the outdoor air like a heat source. The assumed temperature from the heat pump is 45°C and the seasonal performance factor is 2.25 considering the annual electricity need. The solar thermal and heat pump are considered as a unique thermal system.

3.4.1.9 PV system

The optimal tilt angle for Nordic conditions that allows to have the best efficiency of PV panels is around 30 - 45 degrees oriented on South. Nevertheless, the PV was placed on the flat roof and it did not permit to arrange the panels with this tilt angle. It would by necessary having much space to avoid shadowing. Thus, the panels were placed with a tilt angle lower than the optimal one (10-15 degrees) alternating facing South and North. The used module is from the manufacturer SunPower (SPR-333NE-WHT-D), it is a mono crystalline cell type with high nominal efficiency (20.3 %). The module dimensions are 1.56 m high and 1.05 m wide. The panels oriented on South are characterized by a tilt angle of 10°, while for the others oriented Northward the tilt angle is 15°. There are three South facing arrays with ten modules for each one and two North facing arrays with six modules. The total area is 49.0 m^2 for South facing and 20 m^2 for North facing. The annual flux for both panels configurations were calculated: 1 023 kWh/m^2 year for the first group and 777 kWh/m^2 year for the second. The South facing modules produce 8 730 kWh on an annual basis, while the two arrays towards the North produce 2 608 kWh. The total production is 11 338 kWh/year, 71 kWh/m^{2}BRA year. The performance of the PV system has been simulated with PV-syst. During winter, the snow could cover the PV and the efficiency results reduced and in many cases completely eliminated.

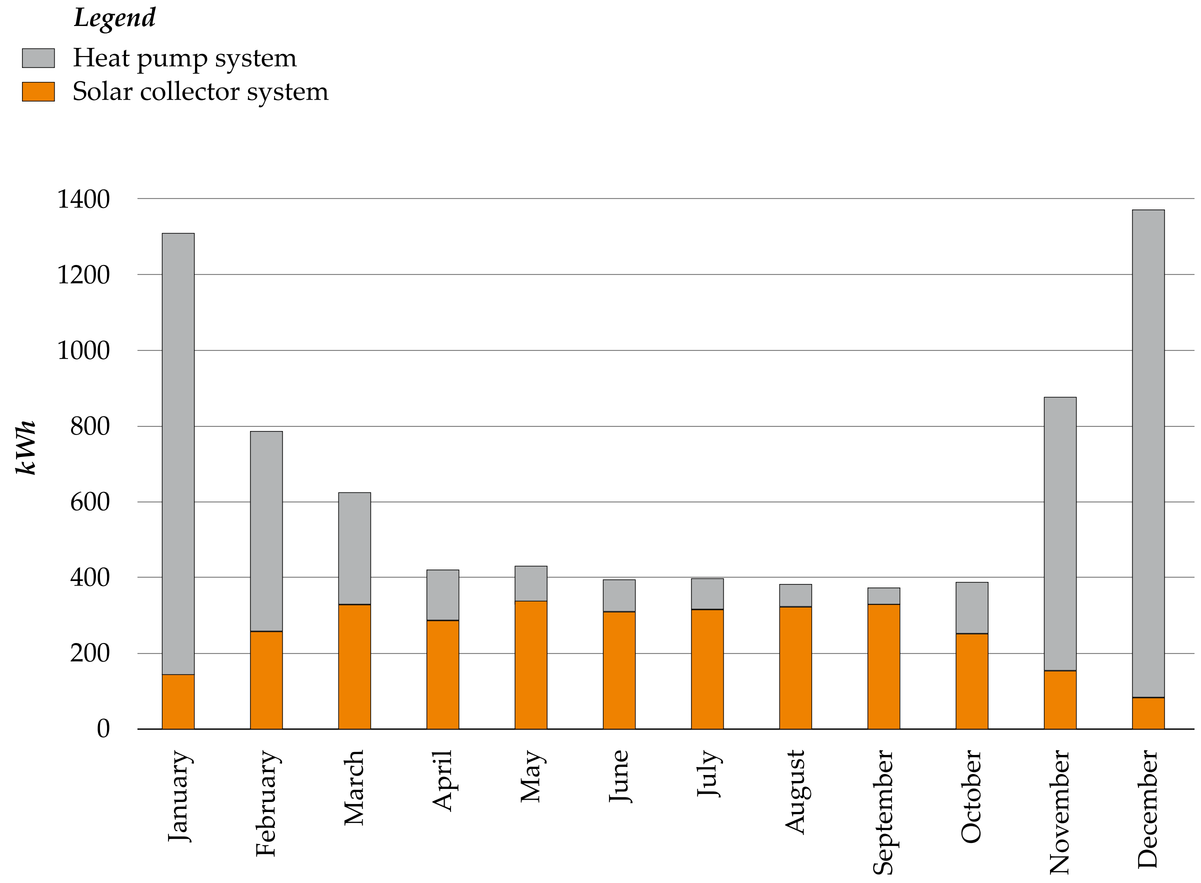


Figure 22 The monthly coverage of the heat demand by the solar collectors and the heat pump (ZEB Project report 21 – 2015).

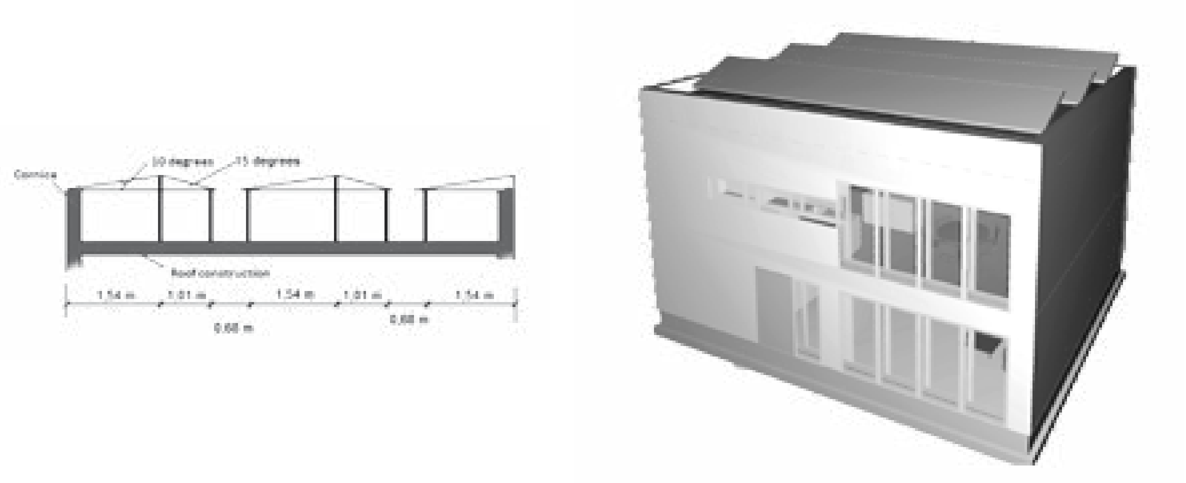


Figure 23 Arrangement of PV on the flat roof (ZEB Project report 21 – 2015).

4.1 PASSIVE APPROACH

4.1.1 Introduction

The passive approach represents the part of the project in which the passive strategies were developed. Before starting the optimization process, some boundaries were defined such as the identification of the main building's properties which could be modified. They are summarized on Figure 24. The most important bond is the approach to the shape; it was decided to maintain it as on the base case model without neither adding nor stealing volume. The box with 10.0 meters by 8.0 meters rectangle as base is a constant in all the models planned during this master thesis. On this chapter, it was paid more attention to the evaluation of materials' impact and the façades' organization such as the size and position of windows. In order to reach a better configuration than the base concept, it is allowed to modify the house's orientation and to change consequently the space's arrangement maintaining the rooms' number and typology. In conclusion, the scenarios evaluated on this chapter are two and they are characterized by the employment of different algorithms for parameterizing the geometry.

4.1.2 Stage 1: building's orientation

4.1.2.1 Building's shell

In this paragraph it is introduced the method employed for evaluating the solar radiation caught by the building's envelope in order to optimize the building's exposure. That process is fundamental for increasing the PV production and also reducing the energy demand for heating the inner spaces. Especially on this stage the increment of SR caught is not counterbalanced with any increment of heat losses because the shell's surface is maintained. The study of the orientation represents the first step toward an eco-friendly planning and one of the most ancient passive strategies applied. The exposure that guarantees the highest value of kWh/year caught by the envelope was found taking advantage of parametric design principles and evolutionary computing theory in Grasshopper environment. The GH's algorithm generates the building's geometry and allows to modify the chosen parameters in order to model different configurations. Taking into account the boundaries summarized on the introduction, the main parameters chosen for being modified are the three dimensions and the angle of rotation that regulates the sun exposure of the box-shape model. The output geometry is simply a box 8.0 meters wide, 10.0 meters long and 6.3 meters high. The rotation angle can be changed from 0° to 90°. All the possible outputs have been evaluated thanks to the two evolutionary solvers compatible with Grasshopper: Galapagos and Octopus. They apply the evolutionary theory to the problem solving, working with genomes and fitnesses. The genomes are the totality of genes, the whole parameters which could be modified in order to create new species. In this case the genome is defined by the rotation angle of the dwelling. On the other hand, the fitnesses represent the ability to adapt of the genomes, thus the ability to solve the problem. In this case the problem is the optimization of the SR caught. The tool's potentiality as solver is the main difference between the two Grasshopper's components. Galapagos is able to optimize only one fitness for each time, while Octopus can work with more than one. Anyway, the advantages and the disadvantages of using the first instead of the second are explained in detail on the tool's review section. At this stage of the process, it is important to know what it is the role of these components on the development of the models. Taking into account the two solvers, in this step of the Passive Approach it was em-

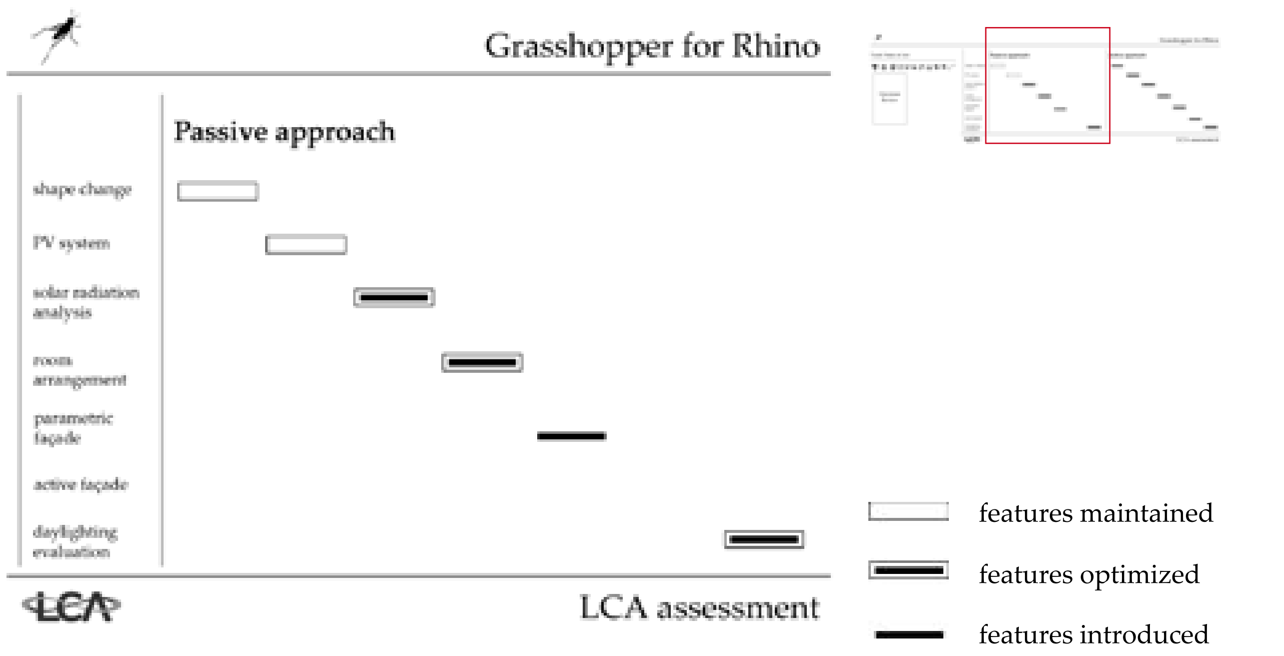


Figure 24 Workflow of the research. In particular, the Passive Approach is organized in six different steps of improvement and during each one, a building's features is maintained, optimized or introduced.

ambient bounces	ambient division	ambient super-sample	ambient resolution	ambient accuracy
2	1000	20	300	0.1

ab *set the number of ambient bounces. This is the maximum number of diffuse bounces computed by the indirect calculation. A value of zero implies no indirect calculation.*
ad *set the number of ambient divisions. The error in the Monte Carlo calculation of indirect illuminance will be inversely proportional to the square root of this number. A value of zero implies no indirect calculation.*
as *set the number of ambient super-samples. Super-samples are applied only to the ambient divisions which show a significant change.*
ar *set the ambient resolution. This number will determine the maximum density of ambient values used in interpolation. Error will start to increase on surfaces spaced closer than the scene size divided by the ambient resolution. A value of zero is interpreted as unlimited resolution.*
aa *set the ambient accuracy. This value will approximately equal the error from indirect illuminance interpolation. A value of zero implies no interpolation.*

Table 14 Settings of Diva for Grasshopper (or for Rhinoceros) parameters used for solar radiation assessments.

ployed Galapagos: the rotation angle was set as genome and the SR as fitness. The tool can optimize a value, but it cannot evaluate that number running the analysis autonomously. Thus, it needs to be coupled with a plug-in that analyzes the SR into Grasshopper environment. The possibilities evaluated on this research were DIVA for Grasshopper and Ladybug. They were compared with the version of DIVA for Rhinoceros in order to have a better accuracy of the analysis. All of them are plug-ins for environmental assessments and exploit the Radiance engine for running simulations. The first step of the analysis is the setting of a grid of test points on the surfaces. It must be paid attention to the direction of the surfaces' normal vectors. In fact, sometime it could be possible that one or more surfaces are oriented toward the wrong direction and the total solar radiation caught by those turns out to be zero. For understanding if something has gone wrong, it is really useful the output generated automatically by Ladybug and DIVA for Rhinoceros. They can paint the surfaces in accordance whit the legend. Otherwise, DIVA for Grasshopper needs to employ the Preview component of GH in order to guarantee the same visual effect. Both the GH's plug-ins give to users the kWh/m^2 caught by each test point through the previously selected period, usually yearly, while only Ladybug can provide the total SR evaluated in kWh/year. Those data could be managed in Microsoft Excel platform. They can be exported through other plug-ins or using directly the *.ill* file generated by DIVA for Rhino's analysis. Although Ladybug could seem more complicated, it is really fast in developing simulations. It is an important advantage considering that the evolutionary solver has to explore a lot of genes' combinations in order to know the fitness's landscape. In conclusion, the fitness connected to Galapagos component should be the DIVA or Ladybug's output if we want to increase the heat gains from sun exposure. At the beginning, it was found the configuration with the highest value of SR on the whole envelope and then it was optimized just the SR caught by two contiguous façades. The same simulations were developed using the *.epw* file of Perugia, Italy, in order to compare the sun exposure at extreme cold and Mediterranean climate conditions. The consequent models were evaluated again in Rhinoceros environment with DIVA for Rhino for verifying the reliability of the previous simulations. Finally, the results were compared to the base case model in order to define some strategies to apply on the next stages. The three considered concepts are identified by the angle of the rotation applied to the base case model. The 0° model is the initial one; it represents the beginning of the optimization process. The 51° model was chosen after the evaluation of the solutions proposed by Galapagos and DIVA for GH. It is characterized by the highest value of SR on two contiguous façades. The last is the one rotated of 90° and it exposes the less extended façade toward South. The analyzed configurations are characterized by the same amount and type of materials employed and it means that no differences can be observed about the embodied emissions. The main difference is related to the heat gains due to the solar radiation caught by the envelope. After a comparison of the analysis developed for each model, it was chosen the orientation that permits to have the most environmentally responsive solution. The preferable exposure seems to be the one guaranteed by the rotation angle of 51°.

In the early stages of the optimization process, the exposure of the original two-storey house was examined in order to find a better configuration or, eventually, validate the original. Thus, the first step was characterized by the combination of the evolutionary natural selection's principles with the improvement of the orientation. It was made possible by coupling the potentiality of Galapagos, which is the evolutionary solver component of GH, wiht DIVA for GH, the tool for environmental assessments. Once it was selected the *.epw* file of Oslo as the weather file for environmental simulation and run the tool, it has been observed that the building's orientation did not condition the SR average during a year. The fitness' values found by the solver were not so different. However, observing the output from DIVA for GH, it is easy to notice that there is something wrong. Actually, the SR average changes although the settings are maintained constant through the simulations: the variation is approximately 2.0 and it should be taken into account while these data are managed. For instance, the optimization with Galapagos found a maximum, but considering the error mentioned above, it is possible to evaluate all the values quite similar, because the values vary from 590.6 Wh/m^2 to 580.4 Wh/m^2 with a percentuage variation of 1.7 %. As previously revealed, it demonstrates how the building's exposure did not influence the SR average which tends to remain constant. Furthermore, the same procedure was followed using *.epw* file of Perugia in order to verify how

tool	component	function
DIVA for GH	analysis grid	set the grid connecting the geometry and defining the grid's cells size, also showing the analysis points and vectors
	material	assign a material to the input geometry
	DIVA daylight analysis for GH	the real engine of the assessment, it permits to manage the context geometry, the weather data, the analysis period and the radiance parameters chosing among several output such as solar irradiation, *kWh/m²* for each test point, and daylighting factor.
Ladybug	open weather file	select and open the .epw file which contains information about climate in general
	analysis period	define the period of evaluation by inserting both initial and final hours, days, months
	genCumulativeSkyMtx	use Radiance's gendaymtx function to calculate the sky's radiation for each hour of the year
	selectSkyMtx	couple the analysis period with genCumulativeSkyMtx component for selecting a specific sky matrix allowing to remove diffuse or direct component from the selected sky
	radiation analysis	Ladybug's engine for radiation evaluation, it has to be connected to the selected sky matrix and the geometry, permitting also to set the north, the grid of test point and the context in order to calculate the SR caught by each test point, *kWh/m²*, and the total SR, *kWh*; the results are summarized in a preview

Table 15 Description of the component included on the tools DIVA for Grasshopper and Ladybug for consucting solar radiation analyses.

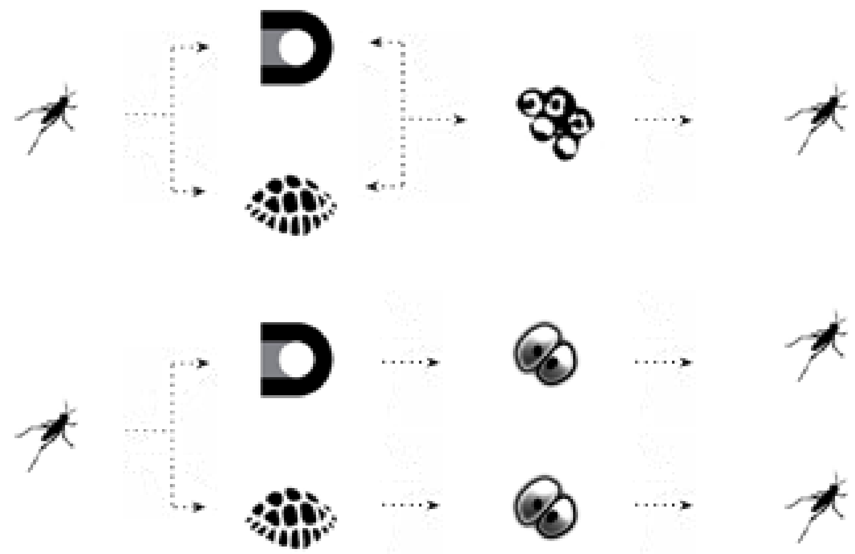
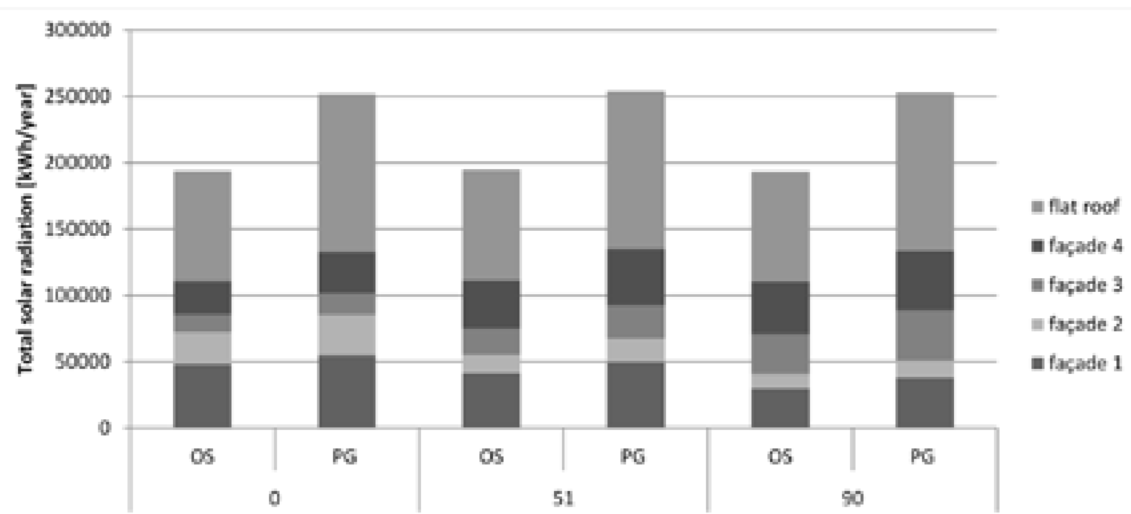


Figure 25 Optimization process. Appling Galapagos and others tools for analysis, it can be reached a different configuration for each analysis. Otherwise, Octopus permits to find the model which optimize both the analysis, in this case Diva and Tortuga.

this first result was influenced by the latitude. The second outcomes highlighted how the latitude did not influence the first, even if it conditioned obviously the magnitude of the averages. The averages found using the Italian weather file were approximately 30.0 % higher than the Oslo's ones. That path did not lead to any best configuration and it seems there are not any preferable solutions. Thus, it was decided to change the approach and optimize the SR average on two contiguous façades. It should allow to find the dwelling with the largest surface which could enjoy the southward exposition. The evolutionary process indicated the model rotated by 51° as the one characterized by the most adapt to satisfy the requests. The analyses were conducted one more time chosing Ladybug instead of DIVA for GH in order to have a confirmation of the outcomes. None difference was found. After that, three different models were selected for being examined in depth with DIVA for Rhinoceros and compared considering both the *.epw* files of Oslo and Perugia. The three chosen concepts are the two extreme solutions, main axis rotate by 0° and 90° from East-West axis and the one with the highest value of SR average on two contiguous façades. The data compared are the SR caught by each surface of the envelope in addition to the totality and the average of SR. These values are shown on Table 16. Observing the SR incoming through each façade, it was realized that the highest value is reached on the roof as it could be easily expected. Despite of it, the two optimized contiguous façades with a South exposure are able to achieve a quantity of kWh/year not so far from the one related to the most irradiated surface. On the other hand, the lowest values can be found on the Northern walls of the house. The original model highlighted how the East and West exposures are similar even if the Western seems to be preferable. Furthermore, the variation between the two set locations is more significant on these last two façades and on the roof's surface because the sunpath change. In fact, the sun tends to be higher in Perugia and it means that these surfaces are exposed for a longer time than in Oslo. The detailed analysis of SR with Diva for Rhino demonstrate that the total incoming heat flux is more or less the same for each model; so improving the exposure of some façades implicates necessarily that the others should be disadvantaged. All the advantages and disadvantages are presented for each model on Table 17. Finally, even if the analyses highlightsed that it was impossible to find the best orientation for the building in order increase the total solar radiation incoming, this study could be relevant for assessments about position of PV and windows on façades.

4.1.2.2 Rooms' arrangement

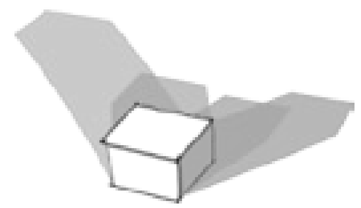
The modification of the building's orientation involves the change of rooms' arrangement. On the base concept, the improvement of rooms' disposition was not studied in depth, in fact the servant spaces were not grouped and in some cases they occupy the best exposure. Although it was not yet evaluated the position and size of glazed surfaces, it was possible to distinguish and locate the two main blocks on building system: served and servant spaces. The firsts are the main zones and the primary areas on a house such as living rooms and bedrooms, whereas the seconds are auxiliary spaces such as kitchen, storerooms, closets, bathroom, circulation and stairs. Observing the shape and the orientation of the model upgraded on the first step, it seems clear that the privileged areas are the ones closer to the southern façades because they catch more SR during the day. Otherwise, the northern area turns out to be perfect for placing there the main servant zones, especially bathroms, entrance and stairs. The bedrooms were placed along the longest façades oriented toward South-East: the light arrives inside during the morning and it decreases during the afternoon. It represents a quite good exposure for bedrooms. On the other hand, the living room was placed on façades oriented on South-West. During all the day it seems to be the place that can enjoy more light. The planning of rooms' disposition should consider also the properties of the outer walls. Two different strategies could be still applied and developed which involves the façades. According to the first approach, the north-exposed façades are more massive than the southern so that they can store the heat which passes through the glazed surface and release it constantly. This was not considered during the development of the original concept even if the window to wall ratio is quite high. In fact, the only openings on the external walls are northward and southward, without windows or doors on both eastern and western façades and no massive wall too for storing heat gains. The second approach prefer to maintain the heat inside reducing the heat losses through the windows' surface instead of increasing the heat contribution as previously explained. The resulting



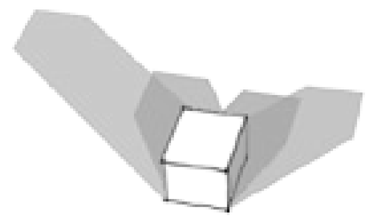
rotation		0°		51°		90°	
weather file		Oslo	Perugia	Oslo	Perugia	Oslo	Perugia
façade 1	*kWh/year*	48 218	54 828	41 115	49 576	29 599	37 949
façade 2	*kWh/year*	24 117	30 921	14 078	17 834	11 145	13 091
façade 3	*kWh/year*	13 678	16 066	19 899	25 184	30 268	37 952
façade 4	*kWh/year*	24 662	30 942	36 293	42 382	39 288	44 675
flat roof	*kWh/year*	83 210	119 095	83 210	119 095	83 210	119 095
total SR	*kWh/year*	193 885	251 834	194 595	254 071	193 510	252 762
partial SR*	*kWh/year*	72 880	85 752	77 408	91 958	68 887	82 624
SR average	*kWh/m² year*	568	737	571	743	567	740

* the partial solar radiation is refered to two contiguous façades. In this case it has been considered the façade 1 and the façade 4.

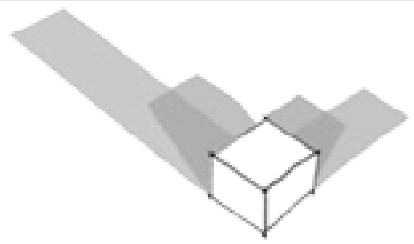
Table 16 Variation of solar radiation caught by each surface, which composes the building's envelope, depending on rotation angle.



Model 1 (longest façade oriented on South)
- ***advantages***: maximum of surface facing to South, so that there can be observed the higher value of solar radiation incoming.
- ***disadvantages***: higher variation of total solar radiation on different façades.



Model 2 (smallest façade oriented on South)
- ***advantages***: lower variation of total solar radiation on different façades
- ***disadvantages***: minimum of surface facing to South.



Model 3 (main axis rotate of 51°)
- ***advantages***: higher value of solar radiation incoming on two contiguous façades, furthermore as much façades as possible can enjoy the Southern exposure.
- ***disadvantages***: having the higher value of solar radiation incoming on two contiguous façades implicates that the other two façades have the lower.

Table 17 Considerations about advantages and disadvantages for each model.

envelope appeared more compact and homogeneus. The openings were defined and located by employing DIVA for GH for calculating the DF and the SR. Actually, the solution applied seems to be a combination of both the ones proposed, in fact the model is characterized by a reduced glazed surface and an increased heat capacity of the northern walls. Anyway, the properties of the shell will be evaluated later, this paragraph is just focused on the rooms' arrangement and the result summarized on Figure 26.

A satisfying level of comfort can be reached also thanks to an adequate rooms' arrangement that is influenced by the building's orientation. In this paragraph the guide lines followed for planning and redesigning the original inner spaces are reported. The space's organization must be in compliance with some good practices such as the location and relation between servant and served spaces taking into account the building and rooms' exposure. The served spaces are the main zones and the primary areas on a house such as living rooms and bedrooms. The servants are auxiliary spaces such as kitchens, storerooms, closets, bathrooms, circulation and stairs. In a well planned dwelling the rooms of the same type are grouped in order to benefit from a similar sun exposure. On the model developed by the Research Centre on Zero Emission Buildings in Trondheim the spaces are organized in two storey with the entrance and the bedrooms at the ground level and the living room, the kitchen and another bedroom at the first level. The relation between function and exposure of the rooms is not considered and that lack could represent a good topic for the optimization process. As introduced on the Felius's report [49], the rooms' disposition could be defined by following a design procedure from inside to outside. The internal layout could be redesigned based on the daily rhythm and movements of persons through the house considering when it would be preferable to have the sunlight in the different rooms. For instance, the bedrooms need to catch mainly the morning sun, so it is more desirable to place them on the eastern areas. As well, the dining room is a zone where people usually spend time together at the end of the day when the sunlight comes from West in the late afternoon. Storage rooms and bathrooms don't need any sunlight, thus they can be placed on the northern areas which receive shadows and diffuse light for all the day. Taking into account all of these principles, the disposition of the base case's zones was redesigned in order to exploit as much as possible the solar gains guaranteed by the improvement of the exposure. The definition of a better configuration of the indoor spaces and the changing of building orientation represented the first step toward the evaluation of the façades and the openings on them. In conclusion, the concept developed following this path was compared to the base case pilot project considering the solar radiation caught.

4.1.3 Stage 2: parametric façade

4.1.3.1 Parametric brick wall

This section is focused on the geometric part of the algorithm that guarantees to apply the parametric design principles to the box-shape model developed by Research Centre on Zero Emission Buildings in Trondheim. As previously introduced, the final algorithms are divided in three main parts depending on their outputs: geometry generation, LCA assessments and environmental analysis. In addition to those there is also the Evolutionary Solver. It is not a part but simply a component and it is chosen between Octopus or Galapagos depending on the needs. This part is fundamental for developing every evaluation and it is the group of GH's components which was modified during the optimization of the base concept. The building shape as it appears is the result of complex analyses and choices evaluated by the architect during the planning. It is influenced by the performance's level that it wants to be reached and the parametric design theory admits the centrality of parameters on the building design process. Robert Stiles's research about the origins of the parametric modelling argues that one of the first architects who write extensively about "parametric" is Luigi Moretti. It was only the 1940 and he had already defined parametric architecture as "the study of architecture systems with the goal of defining the relationships between the dimensions dependent upon the various parameters". Nowadays, these principles start to be largely applied thanks to a lot of software and tools which permit to easily manage parameters and generati-

Figure 26 New rooms' arrangement due to the exposure's modification.

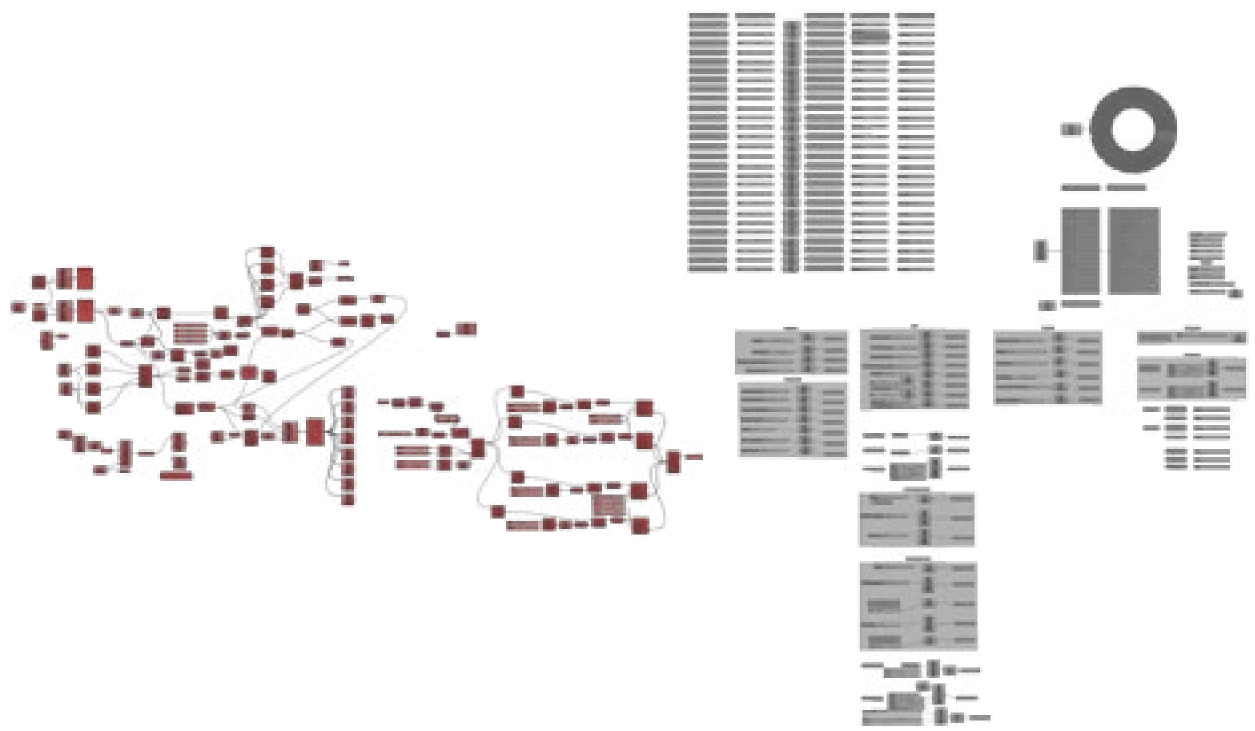


Figure 27 The GH algorithm is composed by different parts. The components colored red are the ones which generate the geometry.

ve algorithms. In this master thesis it was employed Grasshopper. It is a graphical algorithm editor integrated with Rhinoceros 3-D modelling tools. It allows designers with no knowledge of scripting to build form generators easily. The shapes generated can be changed just modifying the input parameters which have to be set before, during the algorithm's creation phase. It is necessary defining the boundaries, input and output values, before starting writing it. In fact, it is not easy controlling everything and it must be done a parameters' selection among the ones which can influence the geometry. A similar path was followed for planning the parametric façade of ZEB pilot project in Oslo. Starting from the wanted output, the necessary input parameters were defined and the algorithm was developed. That stage represents the main approach to the shape on the passive strategies' section. Two different algorithms were created in order to have more than one model for the comparison with the base case. It led to the generation of four alternative configurations from the first and one from the second. Anyway, in this step of optimization just the outcomes from the first are considered, while the other will be later examined in depth. The approach to the envelope's change is limited to the two south-exposed façades. The northerns are just modified on the structure so that they could appear more massive and able to store heat during the warmest hours of the day. Thus, the parametric façade is applied only to two façades southward and it should be built on flat surfaces in order to maintain the box shape. It was chosen the parametric brick wall as the perfect application of parametric design principles to the ZEB pilot project considering the boundaries. It is interesting how that solution permits to create something extraordinary, not common, from one of the oldest material employed for building, the brick. A good example of this type of architecture is shown on Figure 28. Archi Union Architects [50] designed a new façade for the renovation of three old warehouses. The parametric shell is realized using cynderblocks. The rotation angle is different for each block allowing, or not, the indoor lighting. Thus, the necessary inputs for an algorithm which generates a façade similar to this one should be the number of blocks for each line and column, the shift between two consecutive lines and the rotation angle. The warehouses are located in Shanghai, in a climatic zone quite different from the one considered on this thesis. It permits to have a large glazed surface without too much heat losses. Having an envelope completely glazed is not adequate for the extreme cold climate conditions evaluated in this ZEB pilot project. The algorithm should permit to decide between two different types of block: one more massive and insulated, the other glazed and useful for reaching daylighting comfort. Their orientation could not be set manually, but it should be strictly influenced by the rooms' arrangement. That is how the algorithm works. The parametric brick wall is built on a grid of points which allows to change the distance from consecutive bricks and the size of the brick itself (i.e. width, height, thickness). The rotation angle is applied automatically by the algorithm depending on the distance from a point chosen from the grid. A low rotation angle is applied to the nearer bricks. Otherwise, the farers have a higher angle, but never more than 90°. That point could be defined as an "attractor" and its magnitude can be managed through a numeric factor. The application in extreme cold climate zones forces to reduce the glazed surface's area in order to reduce the heat loses. Thus, some of the blocks need to be closed and filled with insulation's layer. The algorithm has to show and consider it when evaluates the daylighting factor. That is managed again through the "attractor points". The nearer blocks are glazed and the extension of this area can be reduced or increased by another numeric factor. The Figure 29 shows how the pattern applied to the parametric brick wall can change consequently to the variation of parameters. The first line represents the modification of the glazed surface, while on the second the magnitude of the "attractor points" changes. On the third line, instead, it was modified the position of the "attractor points" and the last shows several configurations made with different blocks' sizes. A possible development of the façade, which was considered not necessary on this application, is described by Javier Herrero, his research [51] brought him to the creation of a generative algorithm for parametric brick wall where the rotation angle is defined by an image. The result is a wall able to project shadows with the same form of the picture. Anyway, several configurations were generated and compared to the base case just for the CO_2 emissions since the SR does not change considerably. The redesigned model represents the second species that evolves from the original ZEB pilot project. The parametric design principles were introduced applying the algorithm described above. The south exposed façades were built as parametric brick walls formed by cubical modules, each one with the same dimensions but different angle of rotation

input	output
number of elements on columns and lines	*parametric*
shift between two consecutive lines	*built on a flat surface*
elements' rotation	*workable with local materials*
ratio window to wall	
attractor points	***parametric brick wall***

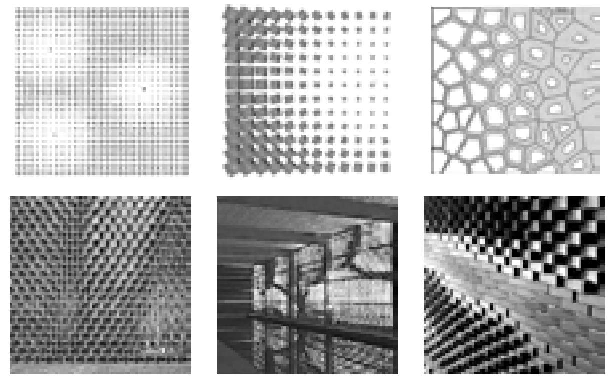


Figure 28 Input and output involved on the algorithm that describes the geometry in this stage of the optimization process.

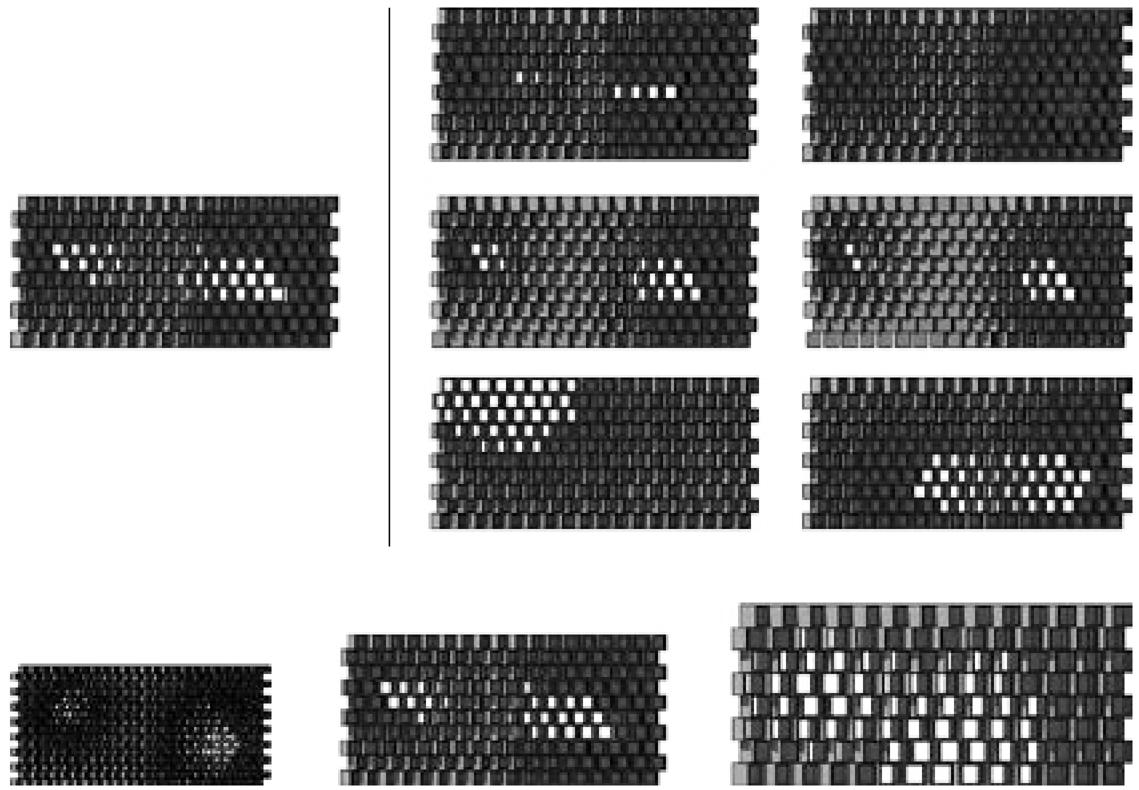


Figure 29 From the same configuration is possible to reach several patterns only modifying one or more parameters, such as glazed surface area, magnitude of points' attraction, points' position and blocks' size.

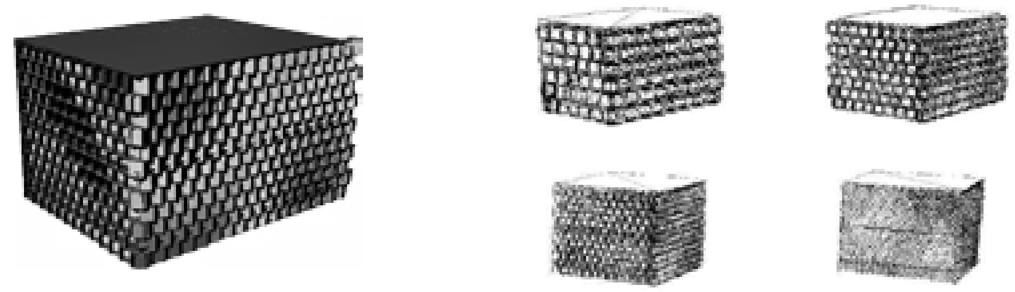


Figure 30 Overview of the different models generated by the same algorithm. The module's sizes are 30 cm, 60 cm, 90 cm, 120 cm.

and they are managed through the GH's algorithm. It allows to evaluate several configurations which were obtained changing the values of the input such as the block's size and the consequent number of lines and columns. Four hypotheses with the size of the block's edge respectively of 30, 60, 90 and 120 cm were planned and compared. Maintaining the same load baring structure and materials, the four possibilities were evaluated considering the embodied emissions in order to select the best one and proceed on the optimization. The model with 60 by 60 blocks appeared the most convenient among the possible hypotheses. Its southern façades are composed by specific bricks designed during this master thesis project. As shown on Figure 30, the brick proposed has a cubical shape and it is delimited by an external framework with a thermal break on the middle. The empty space could be filled with window or opaque structure. It is composed by a layer's sequence similar to the one characteristic of the original façades. The distribution of the blocks depdends on the algorithm's settings. Although it can be employed a double or triple window panel improved with air or other gas like argon between its elements, the transparent bricks compose an area with maximum thermal dispersion. Otherwise, opaque modules turn out to be better insulated because they are filled with a structure made by wooden cladding, wind barrier, glasswool insulation, damp proof membrane and wooden panel. The wooden frame's core has been covered by outer strips realized with different types of wood burned on surface like in some traditional wooden cladding in Norway. This technique originated in Japan, generates a lots of benefits because the layer of char protects the wood from UV and weathering for also 80-100 year. Anyway, the detailed study of their technology and physical properties was not evaluated on this thesis and it could represent a future development of this work as explained on the specific chapter.

In this paragraph, the passive concepts previously introduced are compared considering the solar radiation caught, which remains approximately constant on each model, and the embodied emissions due to both the change of the pattern applied to the façades and the proposed materials. The steadiness of the SR is due to the maintaining during all this phase of the orientation selected on the first stage of the optimization process so that the variations turned out to be not so significant. On the other hand, the improvement of envelope's materials, openings and design led to the achievement of a reduction of the embodied emissions if compared to the original box-shape dwelling. The parametrization of the façades permits to identify several outputs as shown on the previous chapter. In a chronological as well as logical order, the firsts which were compared are the ones generated through the parametric brick wall's algorithm. They are the ones with the southern façades composed by modules with edge respectively 30, 60, 90 and 120 cm long. The Table 18 highlights the reduction of the initial model's embodied emissions guaranteed by all of them, even if it could seem not so considerable. In fact, the emissions were decreased by a a percentage that varies from - 1.18 % to - 3.78 %. The lowest drop is refered to the biggest blocks while the highest corresponds with the smallest ones. The carbon emissions calculated appling the algorithm created in GH environment considering a building lifetime of 60 years and a BRA surface of 160 m^2 were 80 205 $kgCO_{2eq}$ (8.35 $kgCO_{2eq}/m^2BRA$ year) for the ZEB pilot model, 79 267 $kgCO_{2eq}$ (8.26 $kgCO_{2eq}/m^2BRA$ year) for the 120 by 120 cm brick's model, 79 125 $kgCO_{2eq}$ (8.24 $kgCO_{2eq}/m^2BRA$ year) for the one with 90 by 90 cm modules, 78 527 $kgCO_{2eq}$ (8.18 $kgCO_{2eq}/m^2BRA$ year) for the 60 by 60 cm block's concept and 77 281 $kgCO_{2eq}$ (8.05 $kgCO_{2eq}/m^2BRA$ year) for the last one. In order to better understand the drop of the materials' ecological footprint, the emissions' totality has been divided into the contributes from each material. Some of these did not change depending on the model. The elements as the ones which compose the roof and the groundslab or the systems for heating and cooling or PV and solar thermal collectors remained constant on all the hypotheses. The values which are upgraded are the one refered to the elements which have been employed on the façades' structure. All of these values are summarized on Table 18 and reported on the graph illustrated on Figure 33. Observing the data, the windows' frame volume is increased if compared to the original concept. It is due to the choice of including the volume of the modules' frame into this category. Taking into account their desing and features, such as the thermal break in the middle of them, these frames were considered more similar to the windows' one than to the structural timber. Moreover, the $kgCO_{2eq}/kg$ of wood employed on the load bearing structure is lower than the one of the wood used for windows' frame; so the choice explained above could be considered in safety factor. Once the outcomes have been

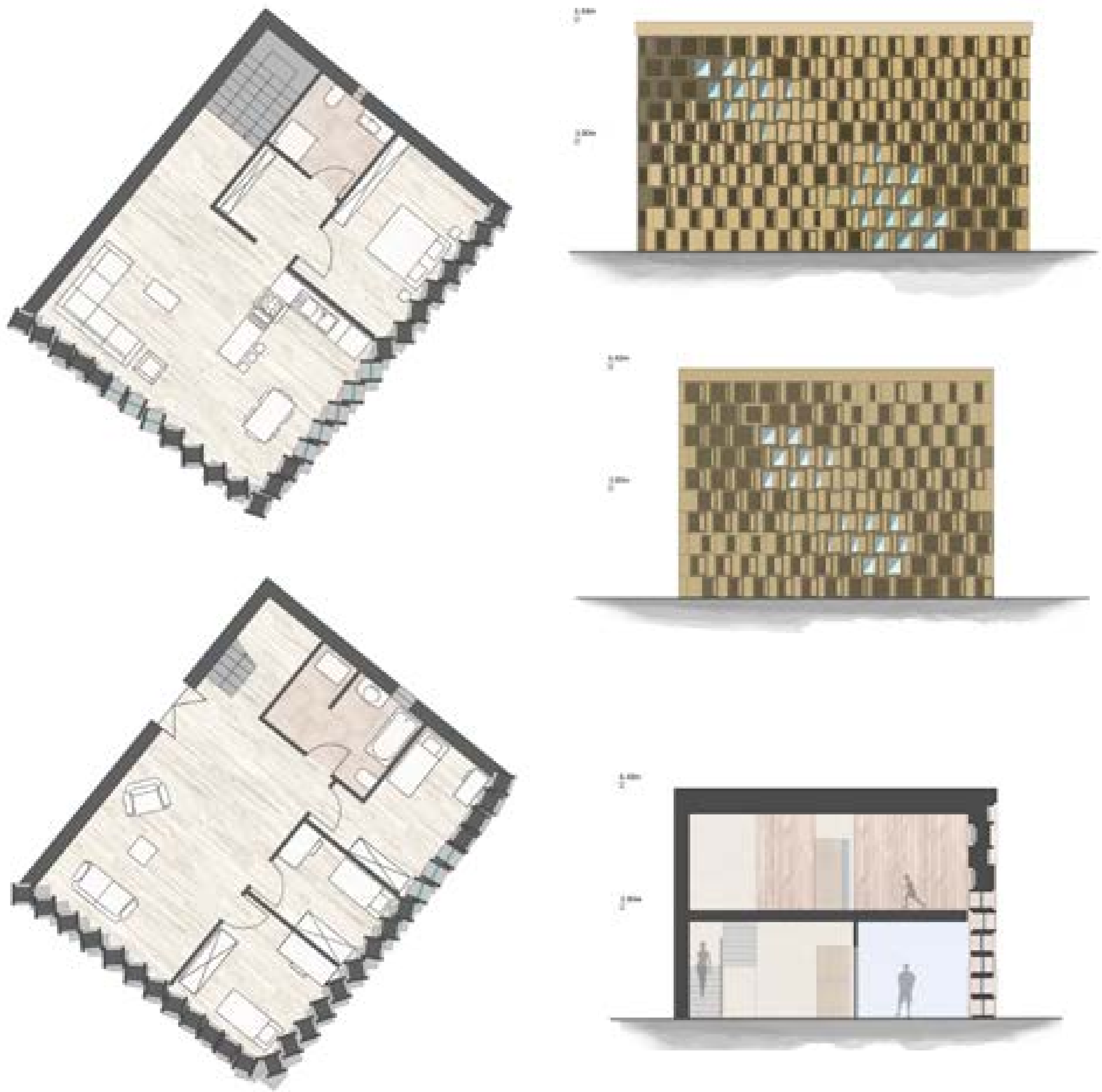


Figure 31 Stage 2. Model developed by appling a parametric façade.

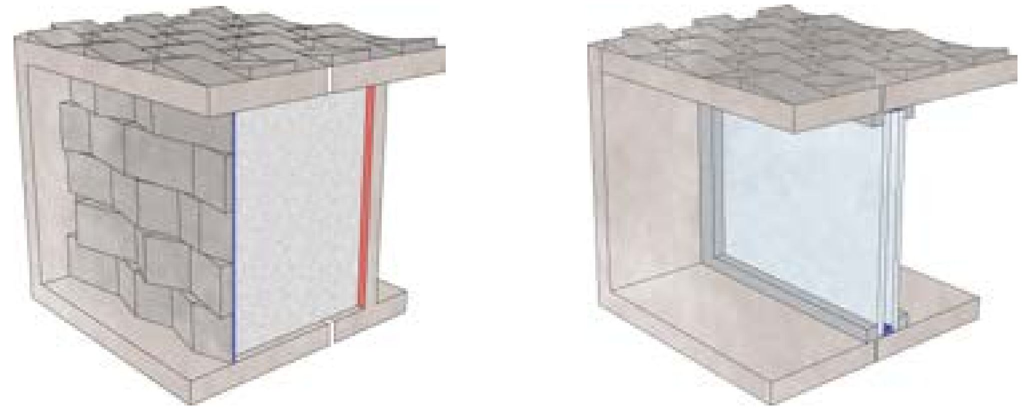


Figure 32 Sequence of layers which compose the modules employed for building up the façades.

compared, it has been selected one concept in order to evaluate the materials previously introduced on the specific paragraph and their impact on the embodied emissions. The chosen model is the one composed by modules with edges 60 cm long. Despite it does not correspond to the lowest value of embodied emissions (E_e), it has be chosen anyway because its modules have seemed to be more adapt than the smallest blocks for hosting windows into their frame.

4.1.3.2 Materials properties

Once the geometry was defined, it has been evaluated the different materials properties which can be used for the whole envelope in terms of Embodied Emissions. The choice of the materials into the LCA process is one of the most important parameter to be considered to control the level of emissions . The base case is a timber structure and the wood has been contemplated also in the new analysis, but for a comparison with different solutions three more hypotheses have been formulated. The new proposals for the materials:

- concrete, for its flexibility, reduct cost, structural properties and long life it is used largely in building.
- auclaved aerated concrete, for a better thermal performance than normal concrete.
- clay with straw (brick), a sustainable materials with a good energy features.

Then the materials have been selected, either for their common application , or for the properties that could improve the passive standard. Advantages and disadvantages were evaluated for each material in terms of ecological footprint and thermal performance. As summarized on Table 20, the concrete has an emissions value of the amount of 0.15 $kgCO_{2eq}/kg$ (263.00 $kgCO_{2eq}/m^3$) and it could be reduced using recycled materials as aggregates. Anyway, the most important problem related to the employment of this material is the low quality level of its thermal performance. The thermal conductivity is just 1.6 W/m K, so it should be coupled with an insulating layer which would

material	unit	model				
		30 by 30	*60 by 60*	*90 by 90*	*120 by 120*	*base case* 8918.08 8707.12
Concrete	$kgCO_{2eq}$	8918.08	8918.08	8918.08	8918.08	1837.57
Rigid Insulation (EPS)		8707.12	8707.12	8707.12	8707.12	900.29
Damp proof membrane (LDPE)		1630.21	1674.19	1677.56	1685.15	1376.00
Parkett Wood flooring		900.29	900.29	900.29	900.29	1438.97
Load bearing Steel Beam		1376.00	1376.00	1376.00	1376.00	6679.49
Timber (Structural)		1352.45	1352.45	1352.45	1352.45	3172.18
Insulation (Glass wool)		6116.44	6315.58	6330.86	6365.22	595.18
Gypsum Plasterboard		3450.88	3482.46	3484.88	3490.33	109.70
Wind barrier (kraftpapier)		479.66	504.13	506.01	510.23	329.52
Door Frame (Wood)		108.52	108.52	108.52	108.52	3436.63
Window Frame (Wood)		1138.04	1853.53	2438.05	2423.23	1762.65
Window (Flat Glass)		2160.18	2372.29	2361.92	2463.54	1879.45
Parapet (Cembrit)		953.43	953.43	953.43	953.43	464.88
Parapet (MDF)		1019.05	1019.05	1019.05	1019.05	12.24
Cladding (wood)		373.33	392.26	393.71	396.98	1780.68
Cladding (wood)_structural desk		12.24	12.24	12.24	12.24	147.16
Ceramic Tiles		1780.68	1780.68	1780.68	1780.68	612.81
Roof membrane (asphalt)		147.16	147.16	147.16	147.16	2279.34
OSB plate		612.81	612.81	612.81	612.81	27860.00
Solar Thermal		2279.34	2279.34	2279.34	2279.34	1301.00
PV panel		27860.00	27860.00	27860.00	27860.00	4578.00
Hot water boiler (OSO EP2 400)		1301.00	1301.00	1301.00	1301.00	1.82
Heat Pump (Boch EHP 7 LW/M)		4578.00	4578.00	4578.00	4578.00	24.88
Heat Pump Refrigirator fluid (R-407)		1.82	1.82	1.82	1.82	
(Heating Sys)PEX - High density polyethylene (HDPE)		24.88	24.88	24.88	24.88	
total embodied emissions	$kgCO_{2eq}$	77281.60	78527.29	79125.86	79267.54	80205.64
	$kgCO_{2eq}/m^2BRA$ *year*	8.05	8.18	8.24	8.26	8.35
variation	%	- 3.78	- 2,14	- 1.36	- 1.18	-

Table 18 The table reported the carbon emission related to each material used on the models developed during the Stage 2.

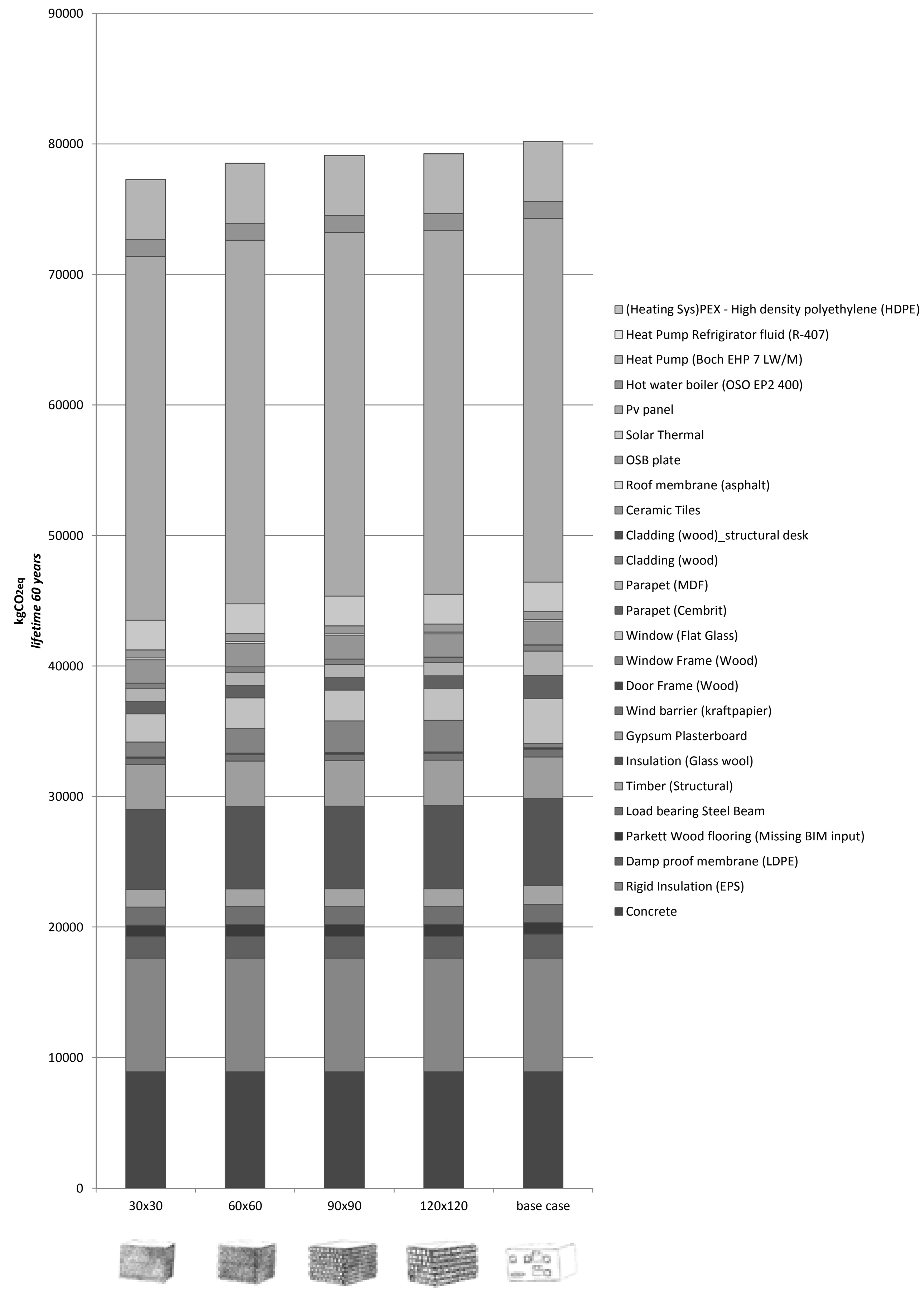


Figure 33 The bar graph shows a comparison of LCA assessments' results for each models decomposing the final value into all its components. The model, from left to right, are: 30 by 30 blocks model, 60 by 60 blocks model, 90 by 90 blocks model and 120 by 120 blocks model, base model.

PASSIVE APPROACH

probably increase the total building's environmental impact. For this reason, other solutions were evaluated. The second hypothesis considers the use of special autoclaved aerated concrete block called Ytong and produced by Xella company, a German factory. During the whole production's procedure natural materials are employed and all the processes are characterized by a low value of carbon emissions. The resulting block is already insulated and it is lightweight too, thanks to the numerous pores inside. Its thermal conductivity is 0.21 W/m K for elements 40 cm thick, while the value of carbon emissions is 0.10 $kgCO_{2eq}/kg$ (191.6 $kgCO_{2eq}/m^3$). The level of performance is very good if compared to normal concrete. Nevertheless, considering the transports in the LCA evaluation, the ecological footprint of Ytong block increases because it is produced in Germany. The variation is so significant that leads to prefer the use of another material that could be a local one such as clay and wood. The first represents an excellent insulating and durable material, which is basically composed by earth. It is cheap and environmentally friendly. Furthermore, it was used extensively for constructions around the world at different latitudes because of its high level of efficiency in presence of damp. Clay has a thermal conductivity of 0.09 W/m K which can be reduced coupling it with fiber. In this way, it could be decreased also the carbon footprint that is originally 0.12 $kgCO_{2eq}/kg$. The last solution is wood, that represents also the structure employed on the base case model. Wood is completely renewable and permits to reach better performance than concrete in terms of embodied energy, carbon footprint and global warming potential. The value of LCA is between 0.09 - 0.13 $kgCO_{2eq}/kg$ and the thermal conductivity depends on the type of wood. In that case, it was considered a value of 0.13 W/m K which is related to conifer. Norwegian EPD data have been used wood wheras for the other material the value of the kgCO2eq/kg are those of the materials technical file provided by companies. Those materials have been later applied to the model with the parametric façades, except the concrete which is clearly the worst among the proposed solutions. On the following paragraphs materials are largely discussed providing more information.

4.1.3.3 Autoclaved aerated concrete - Ytong

The research about the identification of new building materials and technologies are making a lot of efforts to always find something more appropriate to the industry needs. Ytong is a special prefabricated block in autoclaved aerated concrete produced by Xella, a German factory, and developed thanks to one of their research. Its properties represent the result of the combination of a sustainable material with high thermal performance and great capacity for load bearing. This is the effect of a continue research for new building materials with focus on environmental impact. It is reduced giving the possibility to use a prefabricated module and simplify the whole process of constructions. The material's features permit to employ the Ytong on different elements such as insulated building blocks, insulate mats or structural decks making it suitable for a lot of constructive demand. The type of block chosen for the northern façades of the building and analyzed through the LCA assessment is the same considered on the research developed by Rosochacki [52] about the improvement of a TEK10 catalogue house to a passive house standard with different material solutions, comparing embodied emission, cost and energy performance. The element in question is the Ytong Energy+ block, a recent aerated concrete block with a high level of insulating properties which permit to reach a lambda value of 0.06 W/m K when applied to wall 40 - 50 cm thick. It is composed by three layers: two of them, placed on the external surfaces are made from Ytong aerated concrete with a density of 340 kg/m^3, while the core is made from highly insulating Ytong Multipor insulation material (density of 115 kg/m^3). The block in Figure 34 highlights the three different layers and their thicknesses. To produce those modules, just natural materials are employed, easy reachable in nature and the whole process is characterized by a low value of carbon emissions and it reuses almost all the refuses. The aggregates of aerated concrete are made by mixing grind sand with water, cement, lime and aluminum powder. In particular, the last one releases the hydrogen which inflates the mass of cellular concrete creating small bubbles distributed. After the grip the semisolid blocks are cut and hardened by autoclave with high pressure. This phase does not create toxic substances and using water vapor for final hardening process, makes it save a huge quantity of energy. That procedure allows to generate an efficient material characterized by the presence of pores. They are created by the air bubbles into the concrete layer. Its great thermal properties are due to its porosity: the blocks guarantee moisture resistance, low thermal conductivity and good level of load bearing

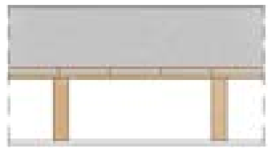
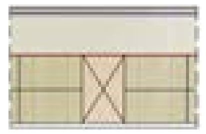
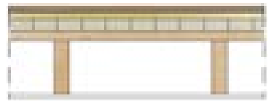
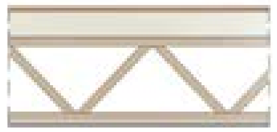
	technical solution for horizontal and vertical closures	U W/m^2K	CO_2 emissions		CO_2 emissions		layers
ytong	roof *asphalt* *insulation - EPS* *damp proof memebrane (LPDE)* *ytong deck* *gypsum plasterboard*	0.09	7 348	0.765	83 871	8.737	
	outer wall *plaster* *ytong energy+ block* *plaster*	0.11	6 918	0.721			
	slab *parkett wood floring* *sponplater parapet MDF* *insulation - glasswool* *ytong deck* *gypsum plasterboard* *wood cladding*	-	4 116	0.429			
clay	roof *asphalt* *insulation - EPS* *damp proof membrane (LPDE)* *clay LaterEnergy* *OSB plywood* *timber (structural)* *gypsum plasterboard*	0.19	5 723	0.596	78 510	8.178	
	outer wall *wood pine cladding* *wind barrier* *insulation - glasswool* *damp proof membrane (LPDE)* *sponplater parapet MDF* *timber (structural)* *clay block* *gypsum plasterboard*	0.13	8 575	0.893			
	slab *timber (structural)* *insulation - glasswool* *parapet MDF* *parkett wood floring* *clay LaterAcustic* *gypsum plasterboard* *wood pine cladding*	-	2 181	0.227			
timber	roof *asphalt* *insulation - EPS* *damp proof membrane (LPDE)* *OSB plywood* *timber (structural)* *gypsum plasterboard*	0.08	6 102	0.636	78 695	8.197	
	outer wall *wood pine cladding* *wind barrier* *parapet CEMBRIT* *insulation - glasswool* *damp proof membrane (LPDE)* *sponplater parapet MDF* *timber (structural)* *gypsum plasterboard*	0.11	8 792	0.916			
	slab *parkett wood floring* *parapet MDF* *insulation - glasswool* *timber (structural)* *gypsum plasterboard* *wood pine cladding*	-	2 314	0.241			

Table 19 The ytong, clay and timber are compared to be used on roof, outer walls and slab.

performance coupled with lightness. All of it permits to reduce the number of constructions layers and joints using approximately just 3 mm of mortar for each one. As previously explained, the Ytong's performances are very good if compared to common concrete. Nevertheless, the emissions value is increased by the transportation because the production is located in Germany.

4.1.3.4 Clay block

The employment of natural resources improves the concept of sustainability for new constructions. An as good as ancient example is represented by the fabrication of clay bricks. Although it could seem an old and outdated solution, it is still an excellent insulating and durable material. It allows to build in a cheap and environmentally friendly way because the soil used extensively for construction around the world is characterized by these properties. Several applications of these bricks can be easily found in Africa and in the Southern part of Europe, with some exceptions in Canada. Thus, the latitude does not represent a limit and it is possible to use this technique almost everywhere. For instance, in the Scandinavian Peninsula the constructions made with clay bricks were really common during 17th and 18th centuries. They used to put into the mixture basically grass, roots and soil in order to realize elements suitable for the building of walls without any mortar. The name of this brick is *adobe* and it is realized in a very simple way that involves only natural materials such as sand, water, clay and straw. The clay dries without any need of getting hardened by firing and it binds the straw together in a rigid mass. The fibers increase mechanical properties and guarantee a high level of insulation. Also the quantity of pores in the clay mixture is fundamental for the thermal performances. A great advantage which should be taken into account during the LCA assessments is the possibility of realizing these blocks in situ with local materials, even if the weather conditions could influence the drying process. Clay protects the fibers from insects, fire, humidity and absorbs odors. The research project developed by Revuelta-Acosta et al. [53] confirms the good thermal properties of *adobe*. It has a low thermal conductivity coupled with a high thermal capacity and this makes the combination perfect to increase the thermal inertia of walls. The earthen houses constitute a green solution and the same research provides a calculation of the energy demand for their construction and maintenance. Approximately 370 GJ per year can be saved preferring that solution to the commoner alternatives. Furthermore, the benefits are not limited to the energy balance but they involve the level of inner thermal comfort and the CO_2 emissions which are reduced by 101 tons per years. The clay bricks are able to absorb the heat during the sunny hours and release the stored energy during the colder period. In this project the *adobe* was employed on the envelope coupled with a timber frame because it has not so good mechanical properties. The clay's mass can increase the heat capacity and the thermal stability. For this reason the bricks are located in the internal part of the walls on the north exposed façades closer to the heat source. The value of carbon emissions is 0.12 $kgCO_{2eq}/kg$ while its thermal conductivity is 0.08 - 0.09 W/m K. The technical solutions chosen for being applied to the clay's scenario were designed considering the proposals of Terragena [54], an Italian factory, which has developed a line of product called Later made of clay. They guarantee that the benefits derived from the clay involve some features of the inner space such as temperature, acoustic, air quality and electromagnetic pollution. In particular, Schneider's research [54] developed for the military institute of Munich demonstrates that a wall built using common bricks made from clay is able to reduce absorb and eliminate the 98% of the radiation generated from an high power electronic system. Furthermore, a layer of clay plaster 2.5 cm thick is able to reduce it of 75%. It could be employed in a lightweight load bearing structure like wood to guarantee other advantages such as insulation, increment of walls' mass and thermal inertia, regulation of humidity and protection from fire.

4.1.3.5 Timber and charred wood

Norwegian architecture is characterized by a constant on its evolution; the use of timber structural solution. It depends on the large presence of wood on the Norwegian landscape and its ease of getting finding, transporting and building. The timber frame is really flexible and easy to adapt allowing to choose among hundreds possible configurations developed over centuries of application. Nowadays, that system is quite widespread among both the conventional and the passive buildings because it is a local material easy to use. Timber has a low conductivity that varies from 0.15 to

	thermal conductivity *W/m K*	*carbon emissions* *$kgCO_{2eq}/kg$*	*observations*
concrete	0.15	1.60	It is possible to improve the performance using recycle materials as aggregates. To define thermal conductivity, it is necessary adding a more insulating layer.
ytong	0.10	0.21	The emissions related to this material should be increased considering that they are produced in Turkey or Germany. The thermal transmittance is referred to a 40 cm thick
clay	0.12	0.08 - 0.09	Coupling clay with fiber makes it possible both reduce the value. The material is completely biodegradable and needs to be protected by dampness in order to reach high level of efficiency.
wood	0.09 - 0.13	0.13	It is a local material, completely renewable. It permits to reach lower levels of kgCO2eq/kg. The physic properties depend on the type of wood chosen; on this case the data are referred to conifers.

Table 20 The table shows the materials evaluated to produce the modules which compose the parametric façade. Focusing on the main ecological and thermal properties, some considerations about the advantages and disadvantages for each material have been explained.

Figure 34 Ytong energy block included an insulating layer in the core of each element.

Figure 35 Sequence of images which describes the process for producing the charred wood

0.75 W/m K depending on the moisture content and it is normally used coupled with an insulating layer. Nevertheless, timber frame buildings do not guarantee a good level of heat accumulation. They heat up and cool down rapidly because of the absence of a thermal mass. An efficient outer wall that permits to reach the standards required by the technical regulations must be composed by several layers, each one with its specific function such as fire resistance, sound resistance, wind proofing, water or vapor proofing, cladding and external protection. Houlihan Wiberg's research [55] on Norwegian passive buildings highlights how it is necessary to employ a layer of mineral wool approximately 350 mm thick in order to reach the performance level required for passive house in Norway. The timber frame was employed on the ZEB pilot project of two-storey house developed by the Research Centre on Zero Emission Buildings in Trondheim. The optimized model with parametric brick walls towards South employs the timber also to build the modules previously described. Those should be characterized by a particular technique applied to the cladding which is explained in detail on the following paragraph.

Charred wooden cladding is quite widespread among Norwegian buildings, ancient or contemporarie. This technique consists basically in burning the surface of wood and it was developed in Japan during the 18th century as suggested by its original name, *Shou Sugi Ban*. During this period, the Japanese builders used to employ mainly two types of wood: cypress and cedar. The procedure is completely natural and easy to apply. Both the sides of wooden plank are burned as much as it is desired to get the element charred. When the wood burns, it starts to be generated an external layer of coal that permits to release the moisture stored into the board's cells such as gas and steam. After a cooling phase, the planks are brushed and washed depending on the wanted visual effect. The quantity of char cleaned off modifies the wood's final aspect. Finally, some applications of this procedure end with the board's sealing. It is realized using natural oil, but this operation is not always necessary. All the stages of the manufacturing process require just fire, water and wood so that it seems to be a perfect passive strategy to improve the wood's preservation. The char layer generates a lot of benefits guaranteeing the protection of wood from UV and weathering for approximately 100 years. In terms of cost, it represents a not secondary advantage because it is very expensive repainting every 10 - 15 years the building's wooden outer cladding. Charred wood is also more resistant to fire and insects, for instance the termites hate this carbon layer. Nowadays, the tradition of *Shou Sugi Ban* has been reevaluated because the architects are searching continuously environmentally friendly and practice solutions to reach a high level of performance for passive buildings. Skanska Group and Snøhetta worked together on the Powerhouse Kjørbo in Oslo [56], a conversion of two existing buildings into an energy-plus building employing a cladding composed by charred wood. As they explained "the project has strived to use environmentally responsible materials from a lifecycle perspective and the charred wooden façade is a perfect example of this". It is realized using natural material that is designed to have a long and relatively maintenance-free lifespan. The application of this system to passive house design gives environmental and structural benefits, but also a final aesthetic effect of charred wood. The resulting pattern seems to be similar to the alligator's skin which changes color during the day varying from silver to black as the sunlight changes.

4.1.3.6 Material and embodied emissions

Once the geometry was defined, three solutions have been evaluted for building up the house: clay, ytong and timber. The timber structure represents the commonest in Norway and the most similar solution to the base case model. The results presented on Table 21 demonstrate that there is

Figure 36 Skanska Group and Snøhetta worked together on the Powerhouse Kjørbo in Oslo, a conversion of two existing buildings into an energy-plus building employing a cladding composed by charred wood.

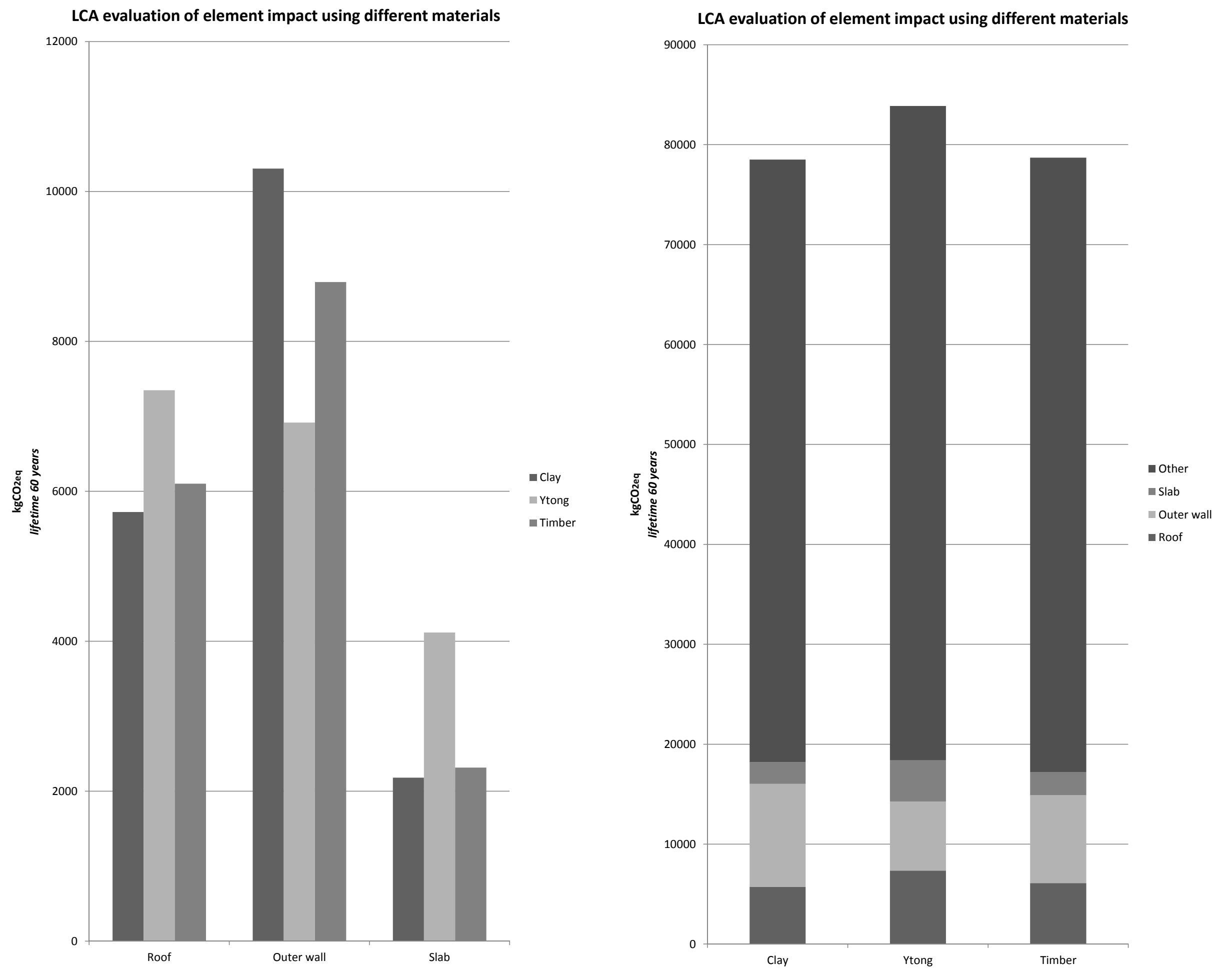


Figure 37 Embodied emissions of the model with the module 60 by 60 cm². They are divided in order to consider the impact of each material on the final result.

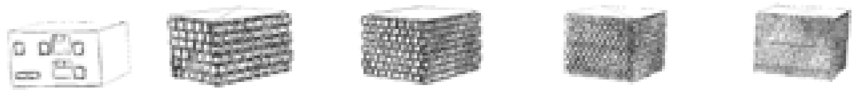
not a huge difference between clay and timber's embodied emissions. Otherwise, the employment of ytong could be quite more inappropriate for reducing the ecological footprint. In fact, the E_e calcuated for a lifetime of 60 years and a BRA surface of 160 m^2 turn out to be 78 510 kgCO_{2eq} (8.18 kgCO_{2eq}/m^{2}BRA year), 83 871 kgCO_{2eq} (8.74 kgCO_{2eq}/m^{2}BRA year) and 78 695 kgCO_{2eq} (8.20 kgCO_{2eq}/m^{2}BRA year) respectively for clay, ytong and timber strucure. The Figure 37 shows a graph with the E_e related to structural elements such as slab, outer walls and roof, which are the ones influenced by the change of material. For example, the groundslab was not modified varing from clay to ytong or something else because in each case it was made from concrete in accordance with the best practices in Norway. Observing the carbon emissions of each dwelling's part it was noticed that the lowest values for both roof and slab corresponds to the geometry coupled with clay, while the outer walls' emissions are hugely lower than ytong's one thanks to the good level of thermal transmittance guaranteed by the ytong block. It permitted to semplify the sequence of layers with no need of to use an insulating layer. In an ideal model built up employing different materials for each structural component, the solutions introduced above should be chosen in order to achieve a level of E_e near to 75 124 kgCO_{2eq} and 7.83 kgCO_{2eq}/m^{2}BRA year. It was preferred to continue the optimization process using just one of the proposed solutions, and the preference was for the maintainance of the timber structure because the information about the material seems to be more accurate and specific for Norway than the others. Moreover, the E_e related to that model are not so high if compared to the lowest value represented by clay, 78 695 kgCO_{2eq} against the 78 510 kgCO_{2eq}.

4.1.3.7 Daylighting and inner visual comfort

Comfort is a users' perception linked to the level of wellness guaranteed by the quality of the environment. Fiorito et al. conducted a review [57] of available innovative shape morphing building skin and their design principles. They provided a complete analysis of visual comfort and how it is influenced by daylight summarizing and comparing the previous studies. Rybczynski [58] described the idea of comfort as an "onion with overlapping layers" because of the continuous evolution of it: each time, a new layer, a new attribute, is added to the previous one. Brager and de Dear [59] highlight the subjectivity of the concept of comfort connecting it to the occupants' satisfaction level which is influenced by the ability to adapt to the surrounding environment. The presence of daylight represents one of the factors that can influence users' adaptation process, and the individual comfort. The studies reported below demonstrate that light is not only necessary for vision, but it is also a powerful modulator of non-visual functions, guarantee of physiological and psychological benefits. Boyce et al. [60] explain for the first time the effect of lighting conditions on healthy sensation. It was shown how people exposed to daylight found the environment more pleasant and showed a better well-being at the end of the day. The research of Aries [61] et al. is focused on the impact of windows and view. It was evaluated the comfort level of users in office buildings in the Netherlands, considering individual and architectural factors such as gender, age, seasons' mood, density of office space, view type and distance from windows. The results demonstrate that the window view is an important factor to improve satisfaction but being too close to the window could be not so comfortable. Boyce et al. [60] published an overview of the lighting impact on humans explaining that it depends on the melatonin which is more efficiently suppressed by lights with higher energy intensity in shorter wavelengths such as daylight is. Thus, the daylight's solar radiation is enough for triggering the circadian rhythm effecting also functions, alertness and memory. Arendt [62] examined in depth the importance of melatonin as marker of circadian rhythm; in fact it is produced only during the dark phase of day. Cajochen [63] summarized several researches in order to define and quantify illuminance levels, exposure duration, timing and wavelength of lighting sources necessary for generating physiological responses in human. The study compared people who worked under right levels of vertical illuminance to people who don't, demonstrating that the second are subject to more fatigue and worse sleep quality. All these studies confirmed how natural light is important to reach a satisfying level of comfort, but in cold climate condition it must be considered also the heat loses caused by an excessive glazed surface. On the base case model, the visual comfort and the daylighting factor, the main parameter that it was used for the evaluations, were not analyzed in depth. It presented a high value of DF average, near to 7.5% while 2.0 or 3.0% could be admissible. During the optimization process, the DF was evaluated on a flat grid of test

structural element	unit	material		
		clay	*ytong*	*timber*
Roof	*kgCO_{2eq}*	5724	7348	6103
Outer walls		10305	6918	8793
Slab		2181	4117	2315
Other		60301	65488	61485
total embodied emissions	*kgCO_{2eq}*	78510	83871	78695
	kgCO_{2eq}/m^{2}BRA year	8.18	8.74	8.20

Table 21 Models' embodied emissions due to the use of different technical solution.



7.52	3.92	2.85	2.65	2.48	%	**daylighting factor ***
34.75	19.05	19.37	19.75	19.98		**ratio window to wall**
40.5	18.0	17.9	13.5	11.4	*m^2*	**glazed surface**
80 205	79 267	79 195	78 527	77 281		**kgCO_{2eq}****
8.35	8.26	8.24	8.18	8.05		**kgCO_{2eq}/m^2 year *****
-	1.2	1.4	2.1	3.7	%	**variation**

* the DF is calculating considering a grid of test points 0,9 mt far from the floor.
** the kgCO_{2eq} is evaluated based on a building's lifetime of 60 years.
*** the kgCO_{2eq}/m^2 year is estimated for a BRA of 160 square meters.

Table 22 The models genereted by Grasshopper alghorithm have been compared considering mainly daylighting factor and kgCO_{2eq}. For a better comparison, the window to wall ratio has been maintained as similar as possible, while the consequent glazed surface's area change.

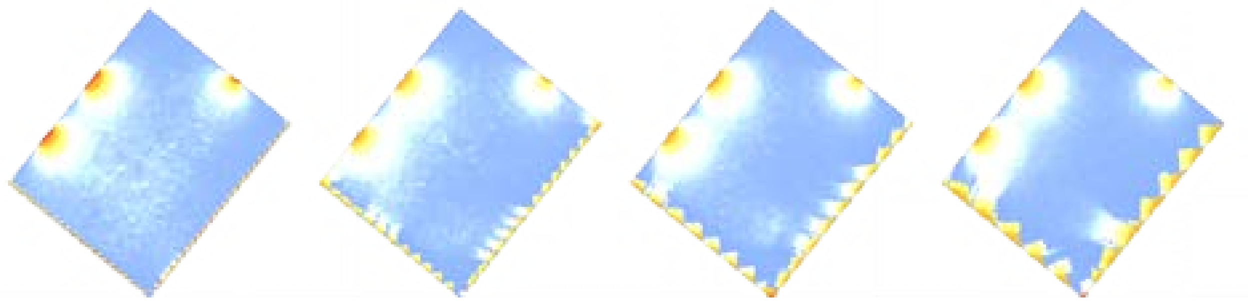


Figure 38 The variation of daylighting factor at the first floor. Increasing the blocks' size, the DF grows from 2,48% to 3,92%. The DF is calculating on work plane 0,9 m far from the floor's surface.

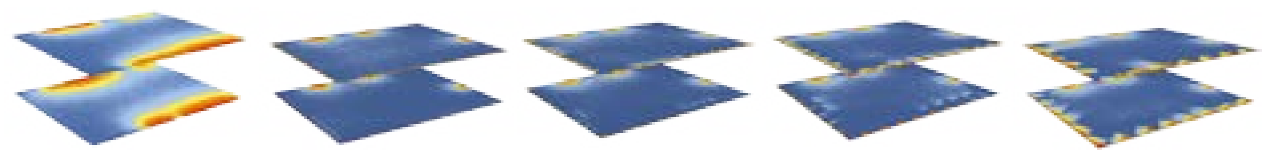


Figure 39 Diva for Grasshopper analysis' output. From the left to the right: base model, 30 by 30 blocks model, 60 by 60 blocks model, 90 by 90 blocks model and 120 by 120 blocks model.

points 0.9 m far from the floor's surface which is the common height of a work plane in a house. The size of the grid lines was set at 0.1 m in order to have a detailed simulation of indoor conditions using the engine of Diva for Grasshopper. The same procedure was applied to all the possible configurations and the analyses' results show how it is possible to reduce the windows' area without causing visual discomfort. Those results are summarized on Table 22, that highlights how it was maintained the same value of glazed surface percentage for all the hypotheses. Those values and the ones about the glazed area are not referred to the entire envelope, but only to the two south-exposed façades, where the parametric skin was introduced. Although this percentage is similar for all the possible configurations, the windows' area, and consequently the daylighting factor, changes. The windows' area and DF reaches lower values , but still admissible, reducing the block's size. It permitted to reduce the quantity of glass necessary for the building and the energy demand influenced by the heat losses through windows. It led to the decrement of the house's $kgCO_{2eq}$.

4.1.4 Stage 3: daylighting assessments

4.1.4.1 Substrate tessellation

The second parametric façade developed on this master thesis involves the whole envelope except the roof's surface. It was designed in order to guarantee a solution for a lack of the previous models. It was difficult to manage the windows on the algorithm explained above and design at least one opening in each room without creating too extended glazed surfaces. It was maintained the organization of the façades. They were divided into smaller modules, but on this algorithm the block are characterized by different dimensions among them. Furthermore, it was fixed the rotation angle so that all the modules are parallels to the façades' planes. To design the texture which divides the shell it was used a GH's component based on the work of Jared Tarbell. Jared's script allows to divide a set rectangular surface in a *n+1* parts tracing *n* lines on that plane. The lines could be characterized by different angle which can be managed easily with a list of input values. It is one of the main inputs of the component as well as the number of lines to draw. Those segments are sketched randomly with a growing density on the center of the texture. David Rutten, a graduate of TUDelft Architecture and Urbanism faculties who works for Robert McNeel & Associates since 2006 on several programs such as Grasshopper development, attempts to explain the function behind the component on his blog [64]. It works one line at a time, the component takes a list of angles and each of them will result in a seeding line at that angle. This is the first step of the algorithm. Once the seedlines have been inserted, one is picked at random and a perpendicular line is created from a random point along that line. This perpendicular line is then, eventually, rotated with a random angle from 0° to the Deviation; this part could be bypassed setting a deviation angle of zero degree. This line is then represented on the diagram until it intersects another line or the boundary. That process is repeated *n* times where *n* is the number introduced at the beginning. The output is a group of lines which divided the space reaching a high level of visual quality, so high that it is used as a base concept for digital artworks. In that application, Substrate of GH is exploited as a random tessellation component to generate a bunch of straight lines, and then the rest of the definition tries to generate boundaries from them creating intricate city-like structures as the one shown in Figure 41. That texture was applied to the façades to generate several cells as a planar base for the modules. They were extruded along a vector normal to the surface with a random length. The Figure 40 presents a prototype published on the blog of Gozour Workshops [65] similar to the one proposed on this paper for the visual effect. In that case the pattern has been easily applied on a cube without organizing it as a building. Otherwise, on the optimized model generated through this algorithm, windows and entrance were obtained into the blocks in order to guarantee a satisfying level of visual comfort into the house. It was evaluated with DIVA for Grasshopper. The approach to the daylighting represents the main advantage of using this algorithm instead of the other one with the parametric brick wall. It is too heavy to be coupled with DIVA for GH and an evolutionary solver such as Galapagos or Octoptus. The analysis of daylighting represents an important step towards the reduction of building's ecological footprint and a fundamental development of the model that guarantees an adequate level of comfort. The quantity of daylight inside the dwelling is measured

Figure 40 Using the Substrate component the simple volume turn out to be more interesting and articulated.

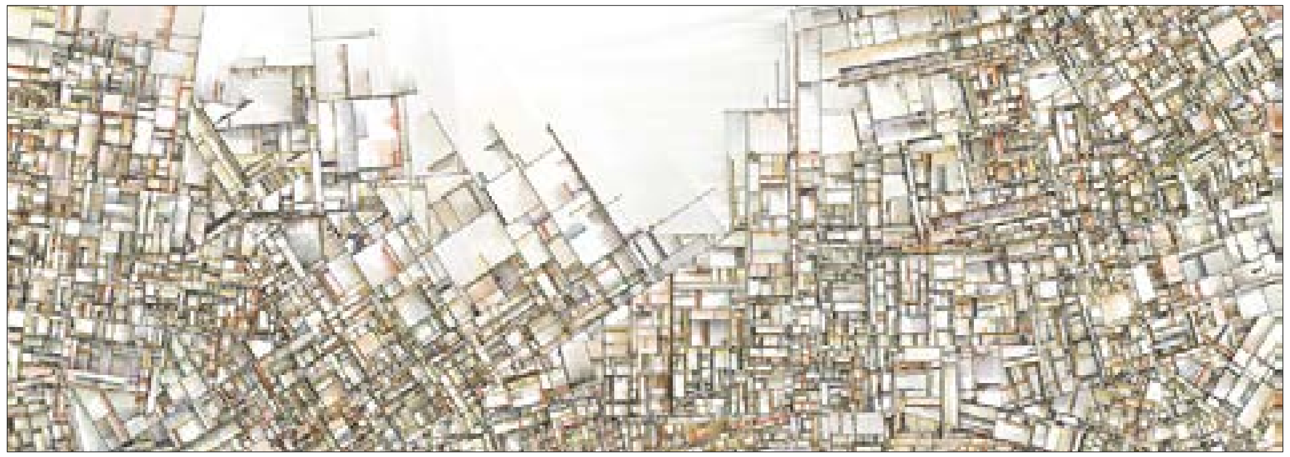


Figure 41 The Substrate component of GH is largely employed also for creating artwork.

with the Daylighting Factor which indicates the percentage of solar radiation that passes through the envelope toward the rooms. Thanks to Honeybee and DIVA for Grasshopper, it is possible to exploit Radiance engine in GH environment in order to calculate the DF of geometry in real time. Although it was considered the possibility of using Honeybee, in this research the DF was estimated by employing DIVA for Grasshopper. It works similarly to the assessment of SR. It was set a grid of test points that represents the workplane, 90 cm higher than the floor's level. Once the sensors were placed, it has been changed the type of analysis from Solar Radiation to Daylighting Factor. The output was modified and the envelope's geometry was connected as DIVA for GH's input because it generates shadows on the workplane. During the SR assessments it was not connected any context geometry because the model is ideal and not located in a specific landscape but just in a latitude and it is necessary for running analysis about DF or SR. DIVA does not permit to have automatically a preview of the evaluation's results, so it needs to be coupled with the Preview component of GH. Once the algorithm which describes the geometry of the building was connected to the DIVA's input, the evolutionary solver Galapagos has been introduced into the GH's canvas. It was set to find the envelope's configuration which permits to have the DF nearest to the Norwegian Standard. The good practices in Norway suggest to maintain the DF around 2.5%. The fitness was introduced on the algorithm as a subtraction because Galapagos can just minimize or maximize a number. Thus, it had to minimize the subtraction between a fix number, which corresponds with the desired DF, and the output of DIVA. In addition to that, it must be added the component for calculating the absolute value of the number before setting it as fitness. Otherwise, the evolutionary solvers estimate the lowest negative number as the smallest value. Finally, the fitness would be the absolute value of the subtraction between the wanted DF and the resulting DF. The evolutionary theory was applied to the windows' planning just on the algorithm at the Stage 3 because it is the only one so light that it could work on the available equipment. In this case the algorithm was set in order to select the cells of the substrate tessellation more suitable to be opened. Once the solver found a better configuration, it has been reorganized manually on Rhinoceros maintaining the same size of the glazed surface on each façade. It was necessary to make the algorithm more flowing and reorganize the location of windows in order to place them at a more adequate height. The daylighting's assessments were developed using only the weather data of Oslo without comparing it to Perugia. That comparison has been realized to highlight the difference about SR caught by the envelope.
The resulting model that permits to have a better control of the openings' size and location is characterized by the smallest required glazed surface. As previously explained, on this case the parameterization involves the whole envelope except the flat roof that lingers as the original one. The four façades were designed through a tessellation of the surface employing the Substrate component of GH. Also the visual effect is completely different if compared to the previous model, although the modules which realize the tessellation are approximately the same previously designed except for the size and the rotation angle. In fact, the modules are coplanar and the rotation is null for each one so that the windows turn out to be less shaded than the opening on the model with the parametric brick walls. The model seems to be more homogeneous and uniform thanks to the pattern that was kept constant on all the façades. The building orientation did not change during this evolutionary step, so the angle of rotation applied to the building is still 51°. Nevertheless, the

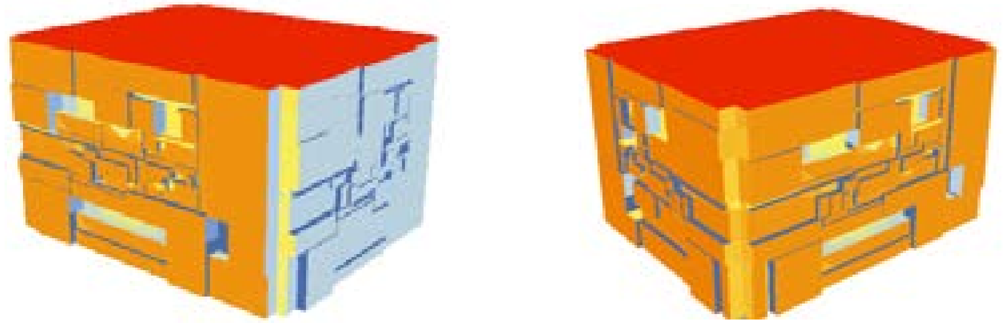
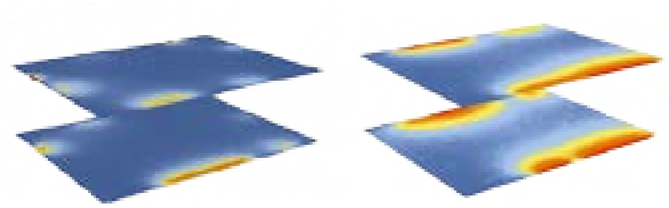


Figure 42 Solar radiation analyses develop with DIVA for Grasshopper.

Figure 43 Stage 3: model developed improving the exposure and the daylightin.

new organization of the windows led to the definition of a different rooms' arrangement as shown on Figure 43. The openings were designed in order to guarantee at least one window on each room. As much elements as possible were located on the South-exposed façades. The consequent glazed surface turns out to be less extended, reducing the efficiency of the increment of heat capacity on the northern walls. After having compared the materials previously introduced, it was decided to maintain the same load bearing structure and layers which compose the outer walls on the ZEB pilot project. The comparison that led to this choice can be examined on the specific chapter. In conclusion, it was evaluated the whole emission balance for the model generated in this stage in order to complete the emissions balance in order to calculate the ambition level achieved at the end of the Passive Approach section. The operational emissions were assessed with Design Builder as explained on the specific chapter about LCA.

As introduced on the chapter about the method applied, once the main material and the dwelling's orientation were defined, another concept has been developed in order to better controll the DF and the windows' size and position without losing the improvements related to the E_e. The pursuit of these goals has led to the generation of the model parametrized using the Substrate component for GH. It was characterized by a reduced glazed surface so that the carbon emissions could be decreased as well. Observing the comparison of the previous parametric brick walls' impact it was noticed that, the models with the most extended glazed surface were characterized by the lowest ecological footprint. In addition to that, the openings' size influences also the operational emissions. All the analyses are presented in detail on this paragraph. The concept introduced in this chapter had



2.52	7.52	%	**daylighting factor** *
5.67	34.75		**ratio window to wall**
11.5	40.5	m^2	**glazed surface**
73 739	80 373		**$kgCO_{2eq}$** **
7.68	8.35		**$kgCO_{2eq}/m^2$ year** ***

* the DF is calculating considering a grid of test points 0,9 mt far from the floor.
** the $kgCO_{2eq}$ is evaluated based on a building's lifetime of 60 years.
*** the $kgCO_{2eq}/m^2$ year is estimated for a BRA of 160 square meters.

Table 23 The models genereted by Grasshopper alghorithm have been compared considering mainly daylighting factor and $kgCO_{2eq}$. For a better comparison, the window to wall ratio has been maintained as similar as possible, while the consequent glazed surface's area change.

structural element	**unit**	***base case***	***substrate model***
Roof	$kgCO_{2eq}$	6103	5441
Outer walls		16233	11751
Slab		2315	2552
PV		27490	27490
Other		28232	26506
total embodied emissions	$kgCO_{2eq}$	80373	73739
	$kgCO_{2eq}/m^2BRA$ *year*	8.37	7.68

Figure 24 Evaluation of the embodied emission from the base case and the substrate model.

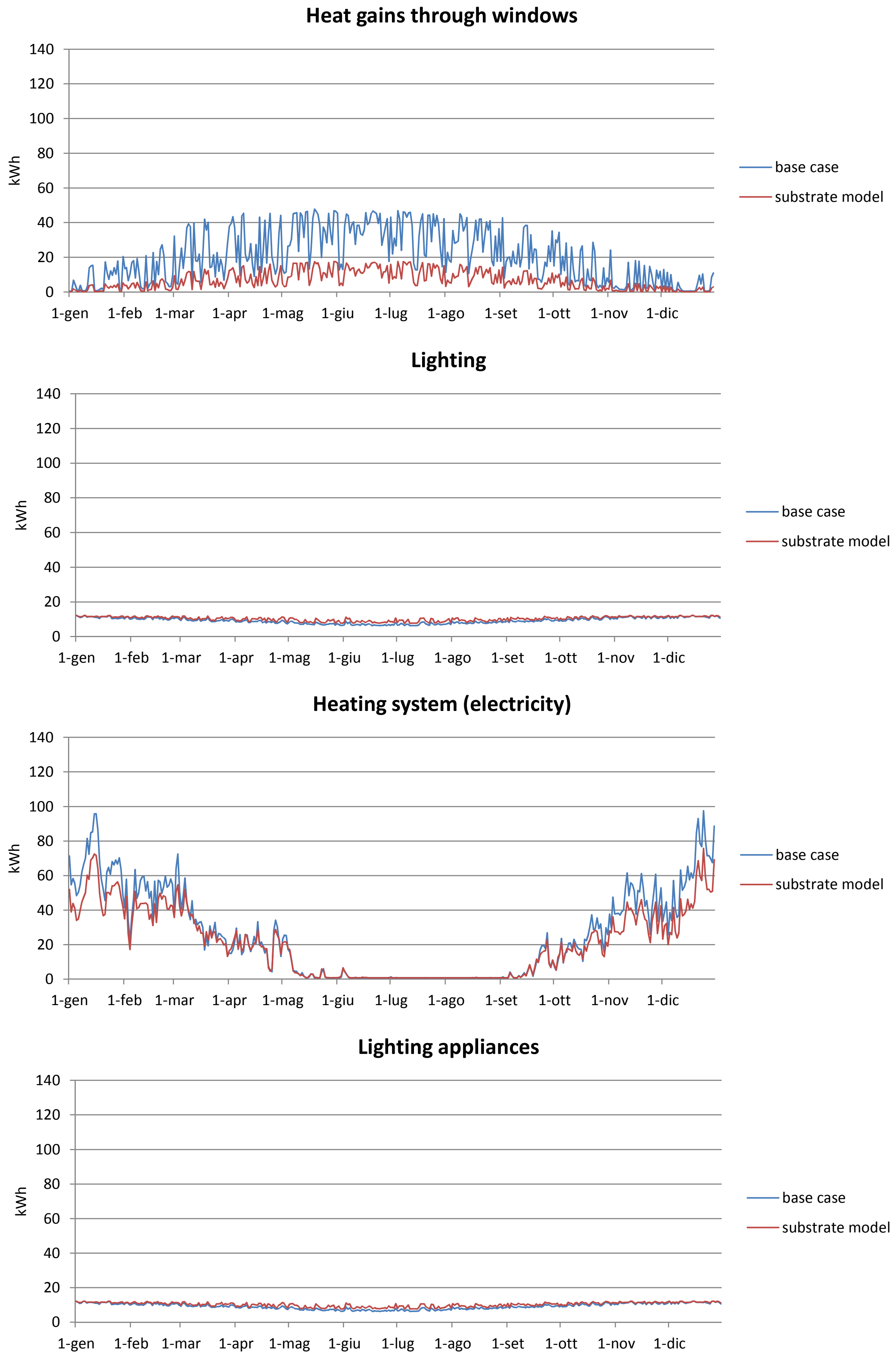


Figure 44 Design Builder allowed to simulate the buiding efficiency and its energy demand.

openings less extended if compared to the original model. Their extension changes from 41.0 m^2 to 11.5 m^2 with a decrement of approximately the 75.0 %. The new arrangement permitted to have an homogeneous distribution of the windows on the façades. As a matter, while the initial model had windows just on the northern and the southern façades, the model optimized on this stage had windows on each façade with a variable ratio window to wall. The ratio depends on the exposure and varies from 9.0 % to 2.0 %. The consequent DF results are lower than the original two storey house model and not so different from the one guarantees by the concepts developed during Stage 2. Otherwise, the different approach to the windows' arrangement permitted to have a better distribution which was not concentrated near an attractor point. The Table 23 shows the results of the DF's assessment. The enhancement introduced during the firsts stages of the optimization coupled with the improved design of the windows allowed to decrease the $kgCO_{2eq}$ caused by the building's construction and operational phase. In fact, the totality of the emissions is 73 739 $kgCO_{2eq}$ (7.68 $kgCO_{2eq}/m^2$BRA year) for the *substrate model* against the 80 205 $kgCO_{2eq}$ (8.35 $kgCO_{2eq}/m^2$BRA year) for the ZEB pilot model. Analyzing the specific data for each element which form the envelope, it was realized that the smaller windows' size makes the outer walls' contribute higher than the one of the base case model and it is due to its more extended surface. It grows from 0.78 $kgCO_{2eq}/m^2$BRA year to 1.22 $kgCO_{2eq}/m^2$BRA year, while the *Other* group which includes windows and their frames goes down from 3.68 $kgCO_{2eq}/m^2$BRA year to 2.76 $kgCO_{2eq}/m^2$BRA year. It produces effects also on the heat gains through the openings which were sacrified to guarantee a reduction of the heat losses and a lower energy demand as shown on Figures 44. The building energy demand estimated with Design Builder appling the method exposed previously achieved a value of 4.60 $kgCO_{2eq}/m^2$BRA year decreasing by the 8.0 % the original consumption that was 5.00 $kgCO_{2eq}/m^2$BRA year. The difference between those two consequent heat gains is more significant in summer as it could be easily forecasted. Having less openings leads the users to increase the use of artificial lighting causing an increment of the lighting's contribute to the heating. In conclusion, on the final stage of the passive strategies' optimization both the E_e and the E_o turn out to be reduced. Nevertheless, the emissions balance shown on Figure 48 highlights how the achievement of the ZEB - OM ambition level is still far.

4.1.4.2 Active development and glazed scenario

On the evolutionary lineage defined on this research, the *substrate concept* represents the last specimen derived from the original ZEB pilot project that maintains the original box shape. In fact, on the next stages it will be improved and the active strategies already applied integrated. The next development is focused on the enhancement of the on-site energy production thanks to the increment of the PV surface, the increase of their efficiency due to the shape's change and the integration with other alternative systems for producing energy on-site such as building integrated photovoltaic system (BIPV) and algae panels. Thus, before starting the optimization of the shape, it was defined a model based on the one developed with the Substrate tessellation where the PV system located on the flat roof was integrated with active façades. Therefore, a BIPV was placed on the southern outer walls where solar thermal collectors were already situated. The application of active strategies as the BIPV is fundamental for reaching the ZEB - OM ambition level and the results are reported on the specific chapter. Furthermore, it was also evaluated the percentage of shell's surface exposed southward that should be covered by this active system. Once the BIPV was located, it has been evaluated the scenario characterized by the as big as possible glazed surface. Basically, the remaining southern surface was redesigned as a continuous window and the model was introduced in Design Builder for developing the analysis about the building's energy efficiency and demand.

As demonstrated by results introduced on the previous paragraph, the concept was not yet able to achieve the ZEB-OM level. That is the reason which led to the evaluation of the improving of PV system adding a building integrated photovoltaic system (BIPV) in order to increase its production even if it should be part of the active approach section. The results, summarized on Table #, show the percentuage of façade which had to be covered by BIPV for reaching the ambition ZEB-OM level. The 100 % corresponds to 105 m^2. From the analyses, it was observed that it is necessary to add approximately a 40 % of the avialable south-exposed façades' surface for realizing a ZEB-OM

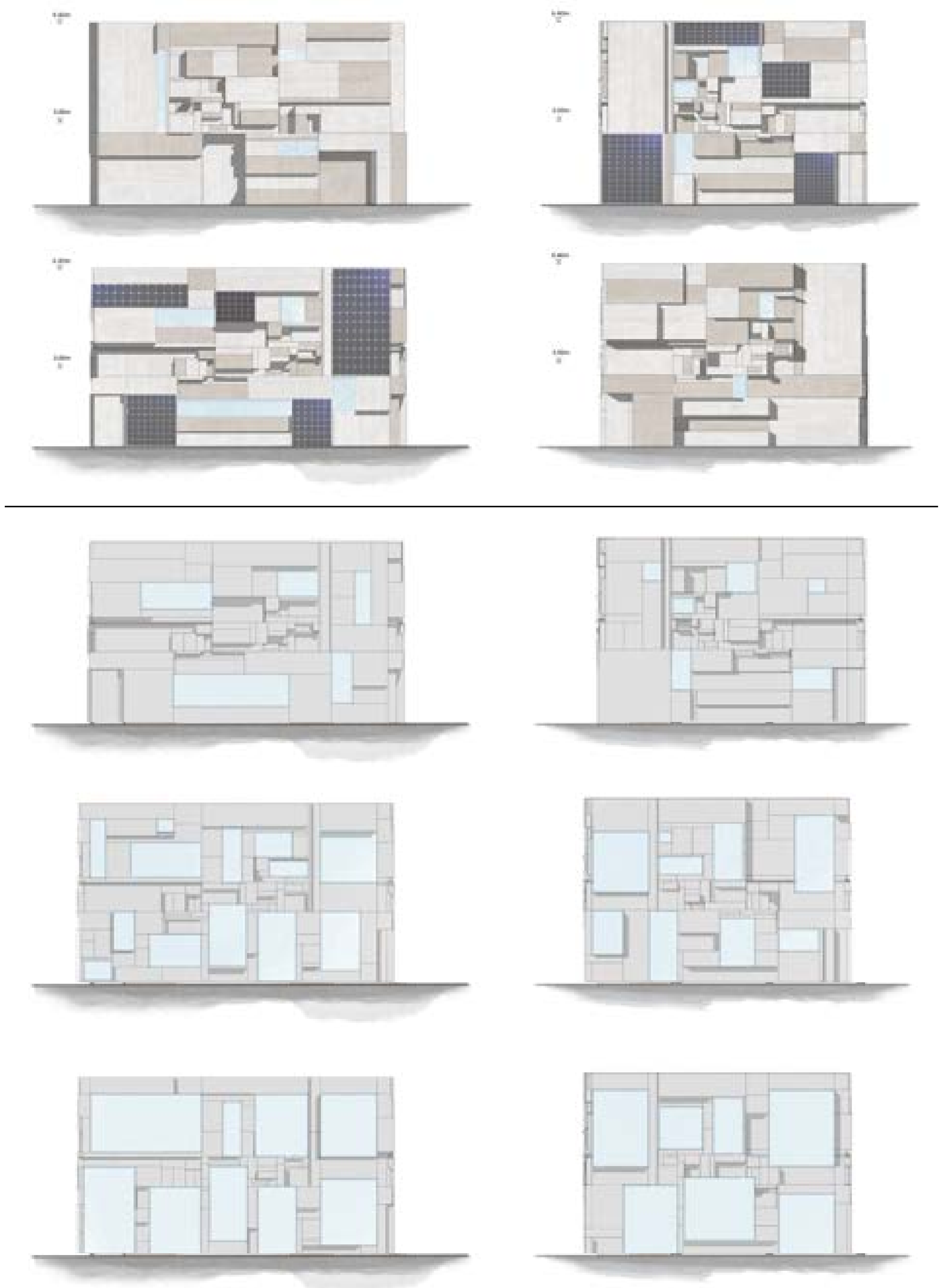


Figure 45 Possible development of the model designed during the Stage 3. The firsts shows the integration with a BIPV system, while the seconds represent the increment of the glazed surface.

building. On this calculation it was included the variation of the E_e due to the BIPV's surface. The blue line wich describes the variation of E_e+E_o is not horizontal. In particoular for each square meter of BIPV, the energy production is 0.12 $kgCO_{2eq}/m^2BRA$ year while the increment of E_e is just 0.04 $kgCO_{2eq}/m^2BRA$ year. As shown on Table 25, covering all the façades southward with BIPV system the emissions balance reaches a positive mismatch of 5.00 $kgCO_{2eq}/m^2BRA$ year. Starting from these considerations, another scenario has been assessed: the model with an increased windows' surface. In fact, until this moment the substrate concept represents the case with the minimal extention of the glazed surface, that guarantees an adequate DF. The increment of the openings can improve the wellness of the inhabitants, thus it was designed a model where the remaining 60 % of southern façades not covered by the BIPV system turns out to be transparent. It permitted to have an idea of the glazed surface's impact on the emission balance. This change influence the whole balance except the PV production which were maintained the same of the first solution evaluated in this paragraph. In particular, the embodied emissions and the operational emissions were calculated considering a 60 % ratio window to wall for the South exposed façades. The ratio's variation from the 8 % of the original substrate concept to the 60 % of the glazed substrate concept produces an increment of the E_e from 7.70 $kgCO_{2eq}/m^2BRA$ year to 9.70 $kgCO_{2eq}/m^2BRA$ year. Moreover, the E_o turns out to be increased from 4.60 $kgCO_{2eq}/m^2BRA$ year to 5.90 $kgCO_{2eq}/m^2BRA$ year. It is due to the

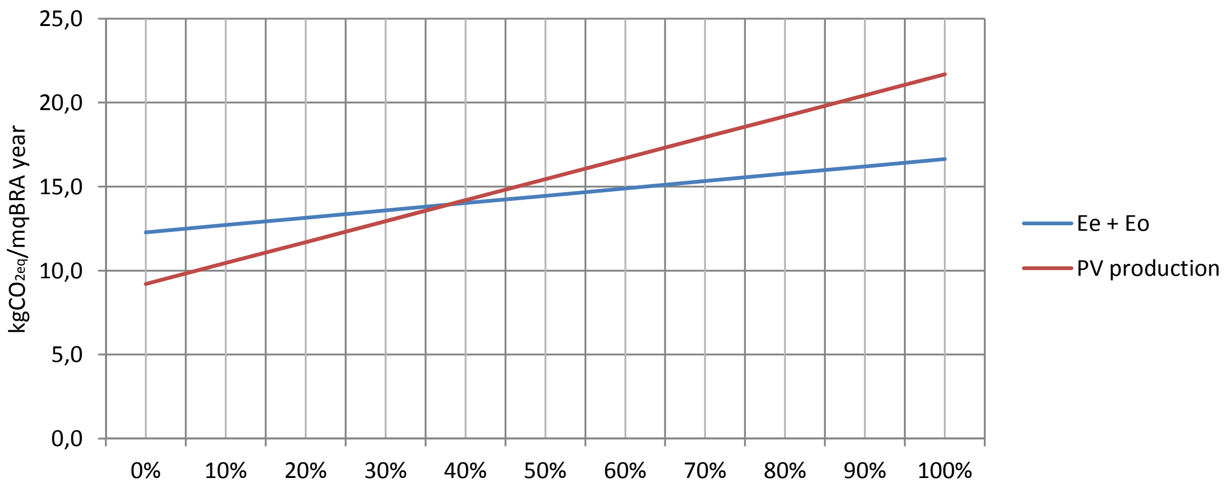


Figure 46 Variation of the emission balance depending on the percentuage of roof covered by PV.

surface available	*m²*						105.0					
existing PV	*m²*						69.0					
PV added	*%*	0.0	10.0	20.0	30.0	40.0	50.0	60.0	70.0	80.0	90.0	100.0
	m²	0.0	10.5	21.0	31.5	42.0	52.5	63.0	73.5	84.0	94.5	105.0
PV production*		9.2	10.4	11.7	12.9	14.2	15.4	16.7	17.9	19.2	20.4	21.7
E_e*		7.7	8.1	8.6	9.0	9.4	9.9	10.3	10.7	11.2	11.6	12.0
E_o*							4.6					
E_e+ E_o*		12.3	12.7	13.2	13.6	14.0	14.5	14.9	15.3	15.8	16.2	16.6
balance*		- 3,1	- 2.3	- 1.5	- 0.6	0.2	1.0	1.8	2.6	3.4	4.2	5.0

* the unit considered is $kgCO_{2eq}/m^2$ year which is evaluated based on a building's lifetime of 60 years and a BRA of 160 square meters.

Table 25 Variation of the emission balance depending on the percentuage of roof covered by PV.

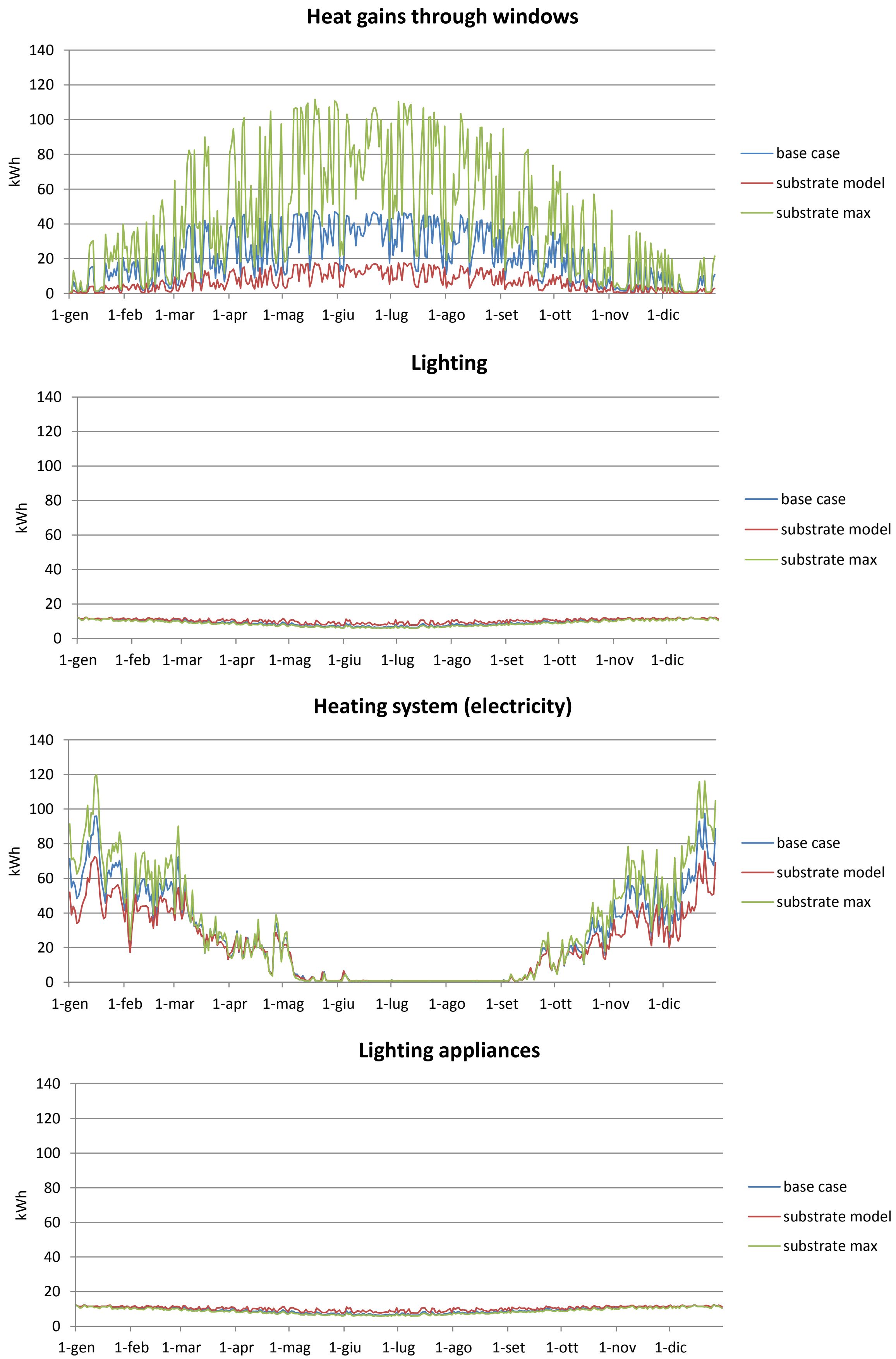


Figure 47 Design Builder's simulation about the buiding efficiency and its energy demand.

growth of the heat losses through the windows and the more intensive use of the heating system as shown on the graphs reported on Figure 47. The consequent emissions balance highlights how the building is not able to achieve the ZEB - OM ambition level, but the mismatch is just 1.3 $kgCO_{2eq}$/ m^2BRA year. Probably it is possible to maintain the ambition level reached on the original substrate model increasing both the glazed surface and the BIPV's area. Anyway, this configuration was not planned on this master thesis and the research turned out to be limited to the two extreme cases.

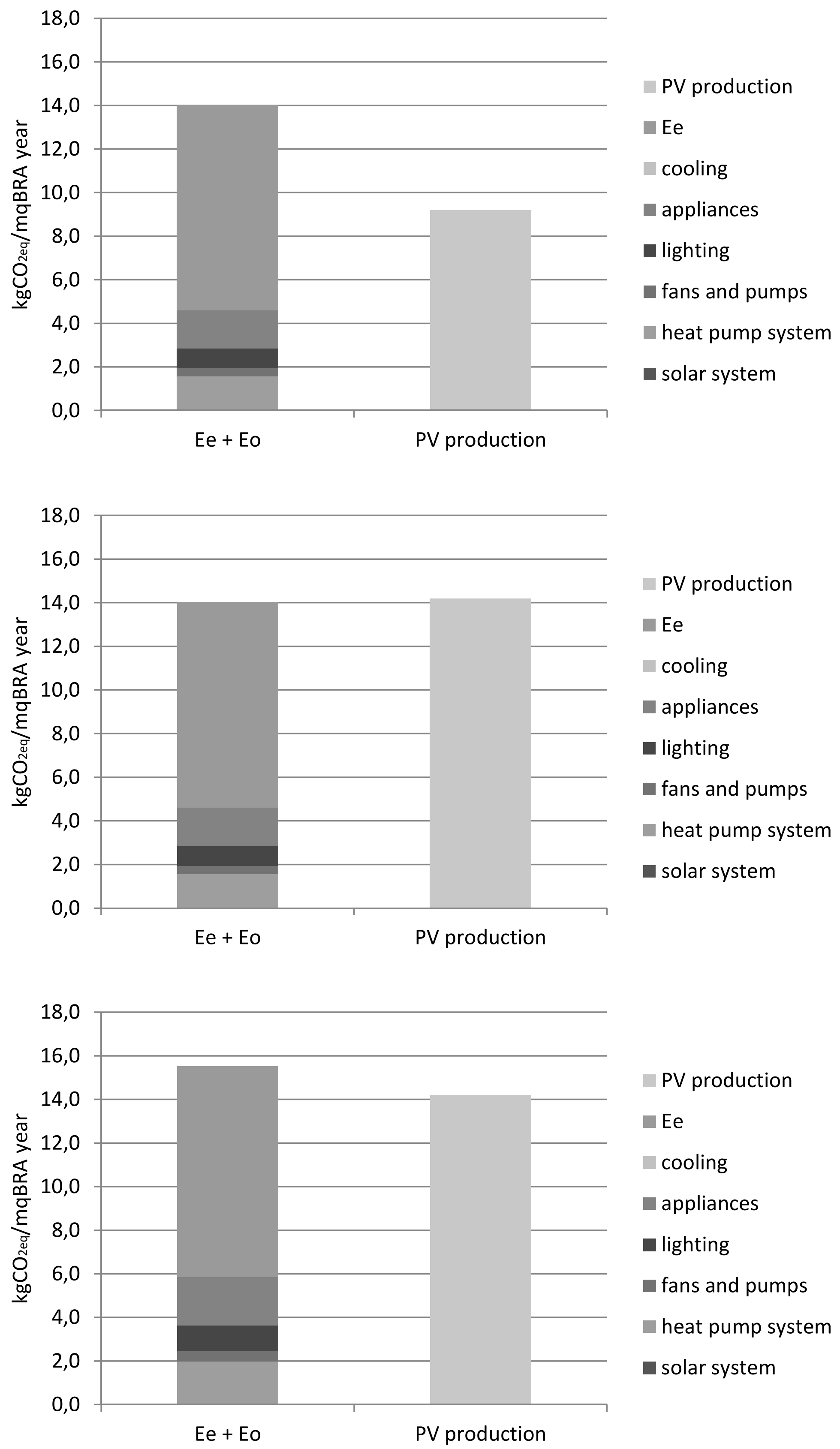


Figure 48 Emission balance of the models included on this Stage: substrate model without BIPV on façades, substrate model with BIPV and substrate glazed model.

5.1 ACTIVE APPROACH

5.1.1 Introduction

On this section, it is introduced the method employed for developing the analyses and compared the results of the Active Approach. Furthermore, some applicable active strategies, which were explored for guaranteeing an improvement of the ZEB pilot project, are presented. This chapter is focused on the boundaries defined before generating those models and the explanation of the GH algorithm created. The algorithm permits to run simulation and generate geometry in GH environment. These are the main design stages considered in this thesis. The algorithms were organized for managing several shapes optimized applying Octopus evolutionary solver instead of Galapagos. The procedure followed for optimizing the shape in Nordic climate condition was repeated in a different context like the Mediterranean environment of Perugia. This optimization represents the first step toward the improvement of the systems for producing energy in situ such as building integrated photovoltaic (BIPV), solar thermal collectors (ST) and algae panels (AP). In conclusion, the level of comfort guaranteed on the previous concepts was maintained as well as the parametric approach. The model developed during this part of the research was not improved step by step as on the Passive Approach, in which the SR, the DF and the CO_2 emissions were optimized separately, adding each time a new request. In this case, all the improvements required above were satisfied by one model. Before generating it, few simulations about the impact of the different building's part on the SR caught were done for having a detailed idea of where the optimization could lead. Thus, the models presented at the beginning represent a sort of preliminary studies about the shape change and the impact of the house's elements on the SR. The second part introduces the forms proposed by Octopus for being redesigned as dwelling and the final configuration based on the one considered as the best among those. In addition to that, the new energy sources considered on the AA such as PV, BIPV or AP, were examined in depth on the last part of this chapter focusing on the efficiency and the technology. The Figure 49 shows the organization of the AA; almost of the features, which are included on that list, were optimized and only two of them (i.e. shape's change, active façade) were introduced.

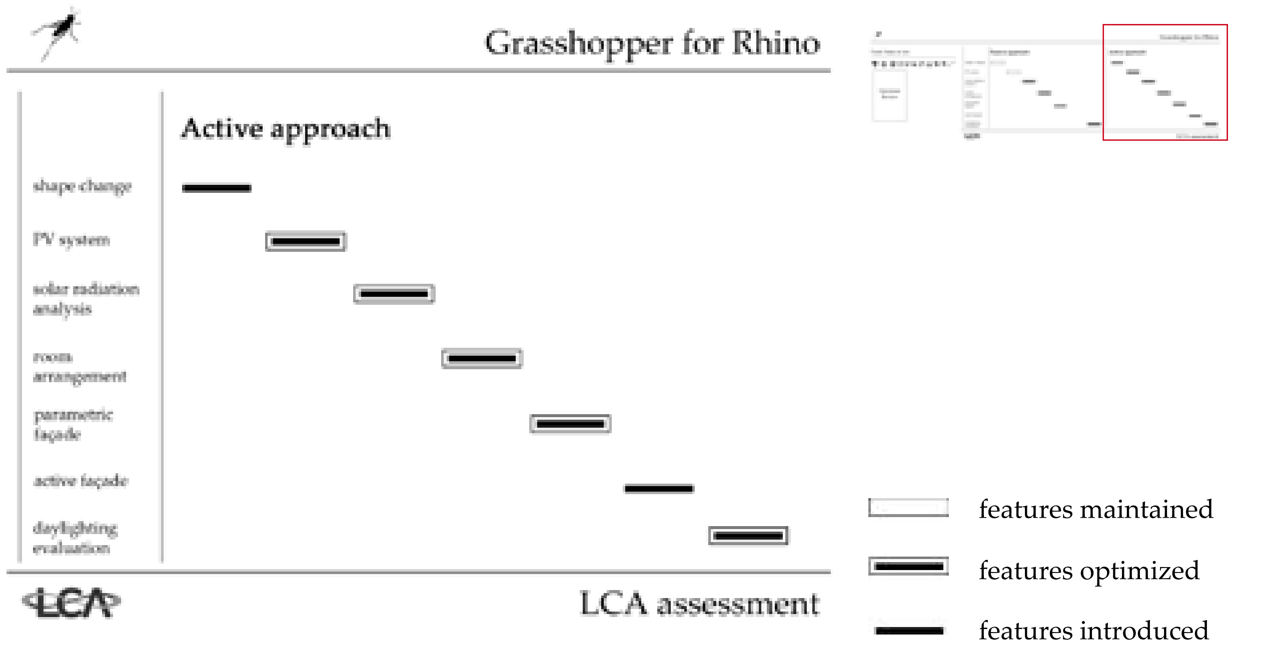


Figure 49 Workflow of the research. As the Passive Approach, the Active Approach too is organized in six different steps of improvement and during each one, a building's features is maintained, optimized or introduced.

5.1.2 Stage 4: shape change

5.1.2.1 Parametric approach

The application of the parametric design principles on the building planning is particularly connected with the shape's change as other steps included on this approach. In this section the process of parameterization is not limited to the façades but involves the whole construction. Thus, the focus is not on the modules which compose the surface, but on the surface itself. The two different approaches could be defined as "micro" and "macro parameterization". The "micro parameterization" is related to the creation of a pattern that can be applied on different surfaces. That type of algorithms permit to manage the main modules' features (i.e. number, density, dimensions, etc.) depending on the needs of the designer. On the other hand, the "macro parameterization" is focused on the building's form and the surfaces which compose the envelope. The two approaches were applied separately, respectively on the first and on the second part of the master thesis. The combination of the two design strategies was not considered in this research, but could represent a possible future development. In conclusion, the parametric principles applied in this section were

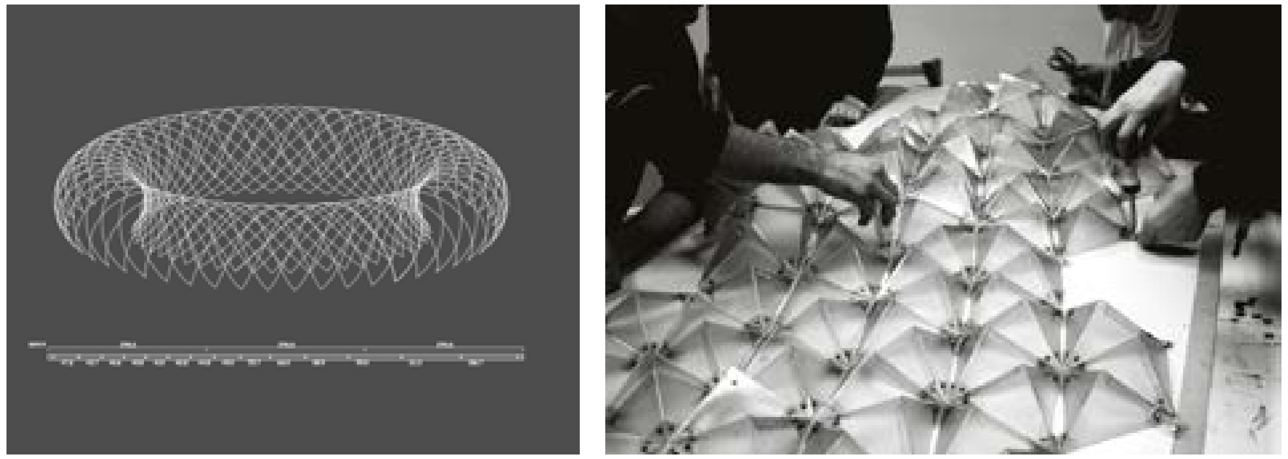


Figure 50 The two images represent the two different approach to the parametrization: macro and micro approach.

well reported on the following paragraphs about the shape's change. There could be found detailed information about the algorithms created with GH.

5.1.2.2 Preliminary studies about shape change

The shape's change represents the core of this part of the master thesis and probably the most completed application of the parametric design principles to the improvement of the original ZEB pilot project. In this stage it was defined an algorithm able to control the whole envelope, while previously the GH model could work mainly on the two southern façades. It can modify the layout according to the considerations and the boundaries chosen at the beginning. The models evaluated were developed as a preliminary approach to the shape's change and they permit make some considerations before realizing the algorithm for the final step. A first approach to the shape's variation was developed focusing on the transformation of the roof. Two types of roof were optimized using Galapagos and DIVA for GH considering only the SR and not the embodied emissions. The building's orientation and the façades' exposure don't influence the total solar radiation caught as shown on the specific paragraph, and the highest contribute is given by the roof's surface. It led to the choice of improving the roof optimizing its exposure. The first transformed dwelling is based on the base case model rotated by 51°. A sloped roof was applied on it and the *z* coordinates of the four vertexes can be changed. Several configurations were analyzed by Galapagos that managed the positions of the vertexes. The results are shown on the specific chapter as well as their discussion. The impact of the transformation on the shape was increased adding more control points in order to generate a roof characterized by a rule surface. Nevertheless, the configuration considered as the best among all the possibilities by the evolutionary solver is the one where the ruled surface turns out to be as much similar as possible to a planar sloped surface. It led to the first important consideration about the envelope: the planar surfaces seems to be better than ruled ones in terms of SR. This assertion will be justified later on the chapter about the results, but it must be considered for understanding the evolutionary lineage that describes the models' improvement. Another test can confirm this hypothesis; it was developed a model with three control points on each edge of the box. The shape was optimized using Octopus instead of Galapagos because of the higher quantities of fitnesses and genomes involved. In fact, in this first test about the approach to the whole building's form, the volume was maintained constant in accordance with the boundaries previously defined. But it was realized applying a minimization of the difference between the new and the old volume so that it represented an extra fitness. The consequent models generated following this path turn out to be totally different among them and absolutely not easy to manage and redesign as dwelling. The increment of control points which permits to have a better control of the outcoming shell does not guarantee better solutions. All of the found configurations are characterized by a high level of geometric complexity. They could be hard to realize and not so advantageous in terms of carbon emissions. Those shapes, more similar to a sculpture than to a dwelling, are represented on Figure 52. Here is the borderline between humans and software: the tools could find the best solution but the architect is free of choosing another or applying only some features to his concept. The tools cannot substitute for the architects, although they represent a useful support.

The building envelope influences the house's energy balance not only for its ability to insulate, but also because its shape is fundamental for optimizing the total solar radiation caught and the efficiency of PV system installed on it. It was evaluated the possibility of modifying the shell's form from the original box-configuration into a new and more complex one in order to further improve the exposure. The main goals were the maintainance of initial volume, and the increment of the total solar radiation caught as much as possible. The firsts aim is really important because having several configurations with the same volume allowed to compare them easily. On the algorithm's language, it was initially translated as a rigid movement of the roof. Moving the roof's surface toward the ground permitted to change the volume in order to maintain it constant. Later it was realized by doing a difference between the initial volume and the final one so that the tool could try to minimize it as fitness. On the other hand, the procedure followed at the beginning for improving the exposure was not too different from the one previously applied with Diva for GH and Galapagos. The only difference is the tool employed for optimization. The increament of Fitness number in the second

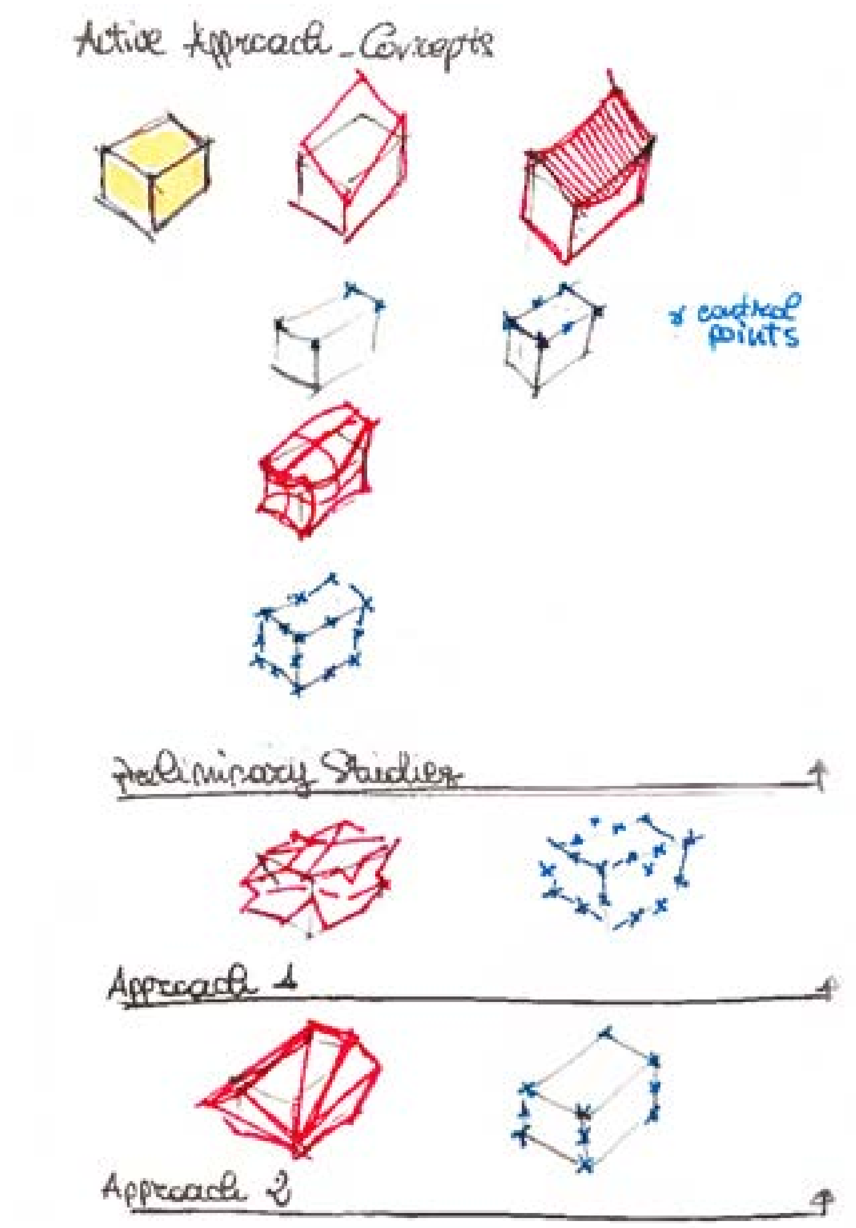


Figure 51 Path followed for generating an environmentally responsive shape for the envelope.

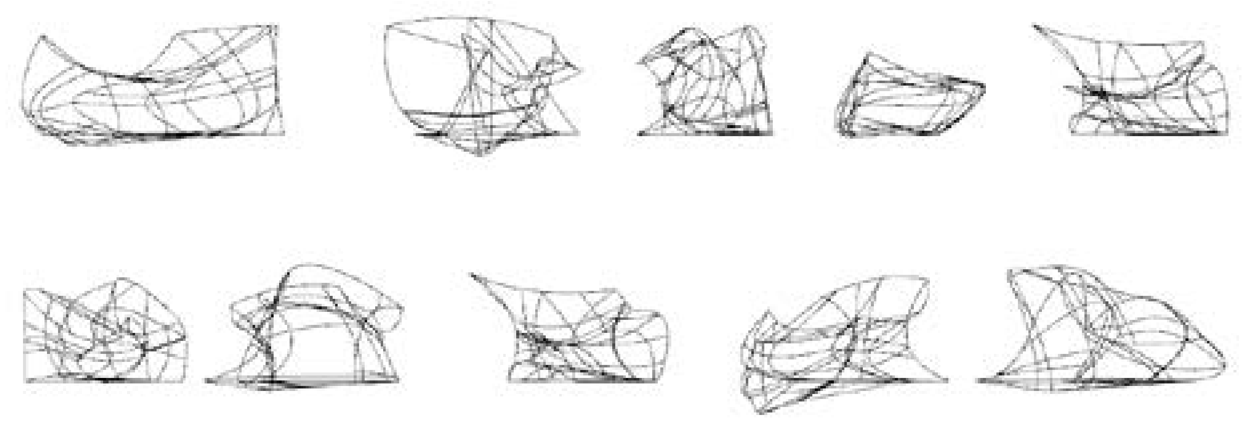


Figure 52 Possible building shell find by Octopus Evolutionary Solver. All the configuration have a similar volume, area and total solar radiation caught. By the way, they seems more a good beginning for planning than a final solution.

part led to the use of Octopus instead of Galapagos. The first approach to the shape change was focused on the roof configuration. The analyses about the SR previously introduced highlighted how important is the contribute of this surface on the building's SR balance. Thus, firstly the possible sloped roofs were evaluated. Among the several possible configurations proposed by Galapagos, a sample of 14 models were selected, 13 solutions in addition to the base case. They had different average values, arranged from the highest to lowest on Figure 53. Table 26 shows a list of these and reportes the consequent average values and the motion vector lenghts for each vertex. The results highlighted that the optimization process was not signifacant in terms of average. It was reached a value of 901.05 kWh/m^2 instead of the initial 863.07 kWh/m^2. The low difference was due to the shortness of the range of value which regulates the movement on *z* axis: Galapagos can change *z* coordinate from 0.00 m to 1.00 m for each point. On this phase it was analyzed the roof's contribution without changing radically the shape as it will be considered later. After the application of the roof on the remainder walls, it was shifted downward so that the volume could be maintained constant. The model with improved roof and the initial model were compared taking into account the total SR and its average on each façade. The improved roof can catch more energy from sun than the flat roof, although the averages were not too different. The average's variation guarantees an increment of the 4.0 %. The roof area was not increased after optimiziation process thanks to the low value of motion vector lenght of each vertex. It represents an important result because allowed to don't increase also the heat losses. Otherwise, on the façades the percentage turned out to be smaller. It was due to the rigid shift of roof toward the ground. In conclusion, a sloped roof could permit to improve the base case model and this betterment is influenced by the tilt angle and the exposed surfaces which should be managed considering the boundaries of the method such as the volume constancy. The process for getting the sloped roof more efficient continued with the change from the flat configuration to the one designed as a ruled surface. In this step the tool was able to modify the *z* coordinates of curves' control points. Those curves were two edges of roof surface and the control points are three for each, two at the extremities and one between them. Giving to Octopus totally freedom of changing those, the main improved configurations found were the planar surface with the greatest slope possible. The results were not satisfying at all; so it was modified the algorithm and set three control points for each edge of initial box. The number of coordinates involved and its range of variation were increased. Octopus managed all of those genes in order to find the local optimum on the fitness landscape. The configurations proposed by the tool were probably too complicated for being used integrally showing the borderline between humans and software. The tools could find the best solution but the architect is free of choosing another or applying some features to his original idea. The tools cannot substitute for the architect, although they represent a useful support. In conclusion, the optimization of the roof revealed that the ruled configuration was not a good solution considering both the SR and the LCA. Thus, it is preferable to plan a building composed mainly by planar surfaces oriented in accordance with the solar exposure.

5.1.2.3 Hourglass concept

The considerations made during the initial tests about the shape change led to the definition of other boundaries about the dwelling's parametrization. It was noticed that a planar configuration of the elements, which compose the building, guarantees a higher quantities of SR. In addition to that, it seems clear that the adjustment of the volume should be managed autonomously by the algorithm without being considered as fitness. Moreover, the structure of the algorithm itself should be reorganized in order to permit a better control of the output. The quality level of the outcomes was increased reasoning on the boundaries. In fact, the quality of the results which could be reached is strictly influenced by the preliminary considerations about the shell as demonstrated by the two different stages proposed in this chapter and examined more in depth below. The first was developed without focusing on the efficiency of the output preferring the aesthetic result. Differently, the other starts from a study of the SR and the envelope's self shading due to its form.

A volume is a geometry delimited by surfaces which are defined by lines or curves. They are managed through a sequence of points and their coordinates. This is valid for basic geometry and particularly for buildings which are composed by façades, edges and vertexes as well. Starting from this, it was designed a dwelling based on the ZEB pilot project of two-storey house. The original

n	average	S	E	W	N	n	average	S	E	W	N
1	901.05	0.00	0.46	0.41	0.99	**8**	863.07	0.00	0.00	0.00	0.00
2	900.05	0.00	0.46	0.89	0.99	**9**	859.15	0.20	0.83	0.93	0.12
3	898.58	0.04	0.71	0.44	0.98	**10**	853.18	0.44	0.48	0.29	0.17
4	896.60	0.08	0.46	0.72	0.97	**11**	840.81	0.67	0.77	0.33	0.14
5	888.14	0.16	0.33	0.30	0.78	**12**	835.45	0.85	0.72	0.09	0.20
6	868.89	0.83	0.83	0.31	0.95	**13**	828.57	0.98	0.13	0.27	0.10
7	863.12	0.34	0.31	0.87	0.32	**14**	825.18	0.98	0.71	0.14	0.08

n *is number of genome. A lower number is related to a higher solar radiation average value.*
average *is refered to the solar radiation. It has been setted as "fitness" for Galapagos Evolutionary Solver.*
S *is the movement on z-axis for the southern vertex.*
E *is the movement on z-axis for the eastern vertex.*
W *is the movement on z-axis for the western vertex.*
N *is the movement on z-axis for the northern vertex.*

Table 26 Evolution of genomes for optimizing solar radiation average.

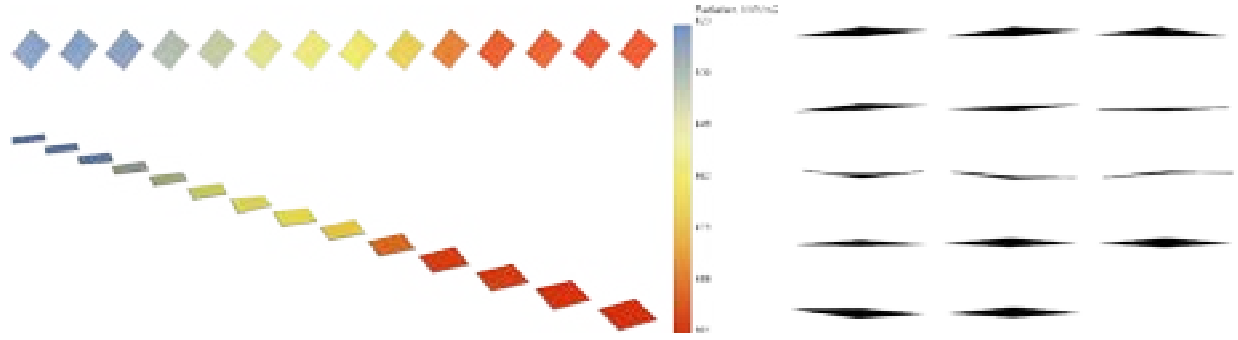


Figure 53 Possible roof configurations found with Galapagos Evolutionary Solver.

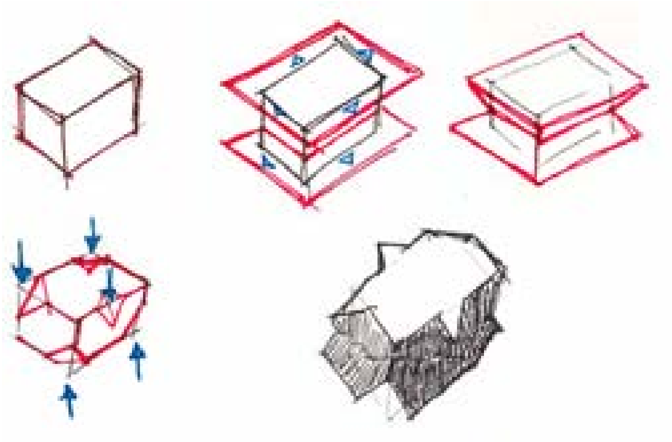


Figure 54 Variation applied to the shape during the Stage 4.

box was decomposed in three surfaces. Two of them are horizontal planar rectangular surface and represent the groundslab and the roof. The third could be evaluated as a loft surface generated between the edges of the previous ones. The loft surfaces are defined by a sequence of profile curves which allow to manage their final shape. In this case the profile curves are the edges of graundslab and roof. They are two rectangles and it is possible to identify four control points placed at the four corners for each one. Those points are the consequence of their coordinates which regulate their position on the space. Once the initial geometry was deconstructed into its components and the parameters which control it was identified, it has been possible to introduce some variations in order to modifying the shell. The first approach starts adding some control points to the ones already existing so that the original rectangles turn out to be two polylines. Contrary to the loft surface which describes the original façades, in this case the loft was not generated through these two curves because a third polyline that connects the midpoints was introduced. After that, it was set an offset distance for the outer curves in order to modify independently the tilt angle of both the upper and the lower loft which composes the façades. In addition to that, it was added a GH component for scaling the geometry impeding the volume's increment so that all the concepts compared could be quite similar. The output geometry is influenced by the parameters, but generally it could appear like a large hourglass based on a rectangle surface and rotate by a set angle. The roof is composed by different slopes and it is possible to modify two coordinates of the highest vertex because the height is maintained constant. The algorithm aspires to manage all of the control points' coordinates in addition to the angle of rotation of the model and the distances of offset applied to each outer polyline. The geometric output was linked to the components for analyses such as DIVA for GH, Ladybug and the specific LCA algorithm explained on the specific chapter. They can respectively calculate DF, SR and embodied emissions (E_e). All of those genomes and fitnesses were connected to Octopus for finding the preferable configuration and estimating the impact of some features on it. Unfortunately, there were too many inputs on Octopus for developing a satisfying analysis, so it had to be reduced the number of both genomes and fitnesses. It means that the grade of parametrization of the building, actually the number of parameters which allow to modify the shell, turned out to be lessened and the consequent transformations were more bound by fixed values. The Figure 55 shows the early stage of the concept design highlighting the control points' positions and the respective axes along which the movement is allowed. It was created an algorithm that permits to manage the building's envelope in order to maximize the SR and minimize the E_e, or at least find a good compromise between them. The geometric algorithm introduced above was integrated with Octopus in order to have a huge quantity of outputs for the comparison. The models proposed are shown in Figure 36. They represent different layouts of the same concept. The idea is to deconstruct the envelope dividing it into two boxes. The outer one is modified in order to permit to see the inner in some parts of the shell. That transformation is based on the Slovenian Pavilion at EXPO Milan 2015 shown on Figure 57. The outer box was deformed applying the variation reported on Figure 54. It is a combination of two approaches. The first is focused on the relation between the inner and the outer box, while the second considers only the outer modifying its configuration from the original box to the hourglass shape. The outer wooden layout could be used for placing the BIPV system while the transparent surfaces could be partially covered by algae panels. Anyway, the developed concept did not permit to reach an improvement on the SR caught and probably also the E_e were not so satisfying. It is due to the wrong premises on which the algorithm is founded. The concept was still too influenced by the original box shape and it represents a limit on the optimization process. That is the main reason which led to the definition of another model starting from a new, even if not so different, point of view.

The algorithm created in this stage of the process was composed by a geometric part and one about evalautions. The first was already described, while the second about assessments and their results is the core of this section. The variables which could be managed by the solver were a lot as well as the evaluations, such as LCA, SR and DF. The solver chosen for being introduced on the algorithm was Octopus. It guarantees the optimization of more than one fitness as previously explained. Although it is more powerful than Galapagos, it turned out to be not able to work with all of these genes and fitnsess. The reduction of the genes' number and the exclusion of the DF from the fitness allowed

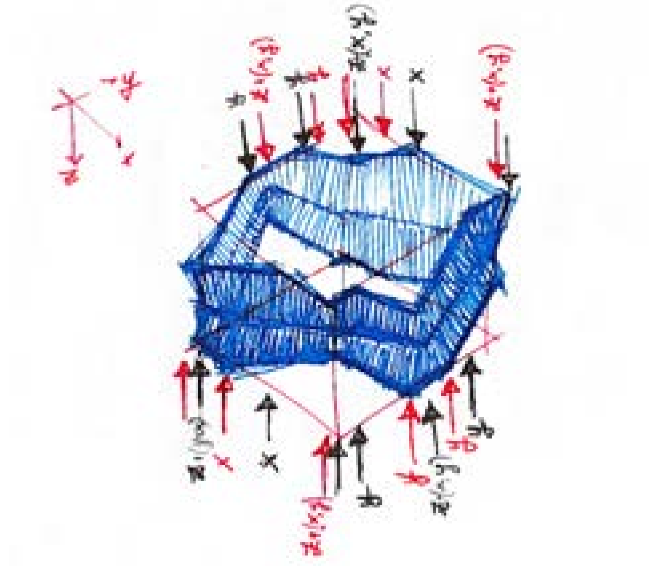


Figure 55 Definition of the vertexes and the parameters managed by the algorithm.

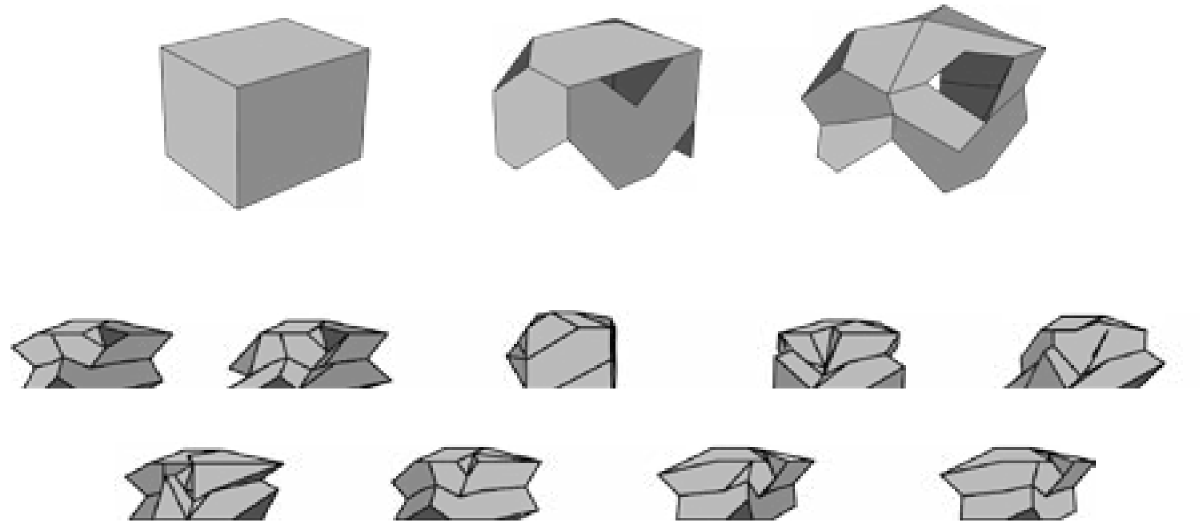


Figure 56 Possible building shell find by Octopus Evolutionary Solver.

Figure 57 Slovenian Pavilion at EXPO Milan 2015.

to continue the process and apply the evolutionary solver to the algorithm. As Galapagos, Octopus analyzed the possible combinations of genes in order to find the best solution. The genomes were drawned on a graph which permitted to choose the solution and insert its genes into the algorithm. An example of the Octopus's interface is reported on Figure 58. The diagram shows the distribution of genomes, which were generated by the solver at the stage described in this paragraph. The solver was set so that it should minimize the fitness and place the most adapt solution in the area near the origin. Thus, the fitness that represents the solar radiation is not the SR itself but its inverse, in mathematical terms. It is quite interesting to evaluate also the distribution of the solution in order to understand if there were some problem on the application of the process. For instance, on the Figure 58 the genomes are grouped almost on the same part of the plane except few of them which are placed nearer the red axis. It represents the axis of the SR while the green is the one about E_e. It means that those exceptions are characterized by a low value of emission and that reduction seems to be significant. Anyway, observing the layout it was noticed that for the solutions nearer to the red axis the part of the algorithm that generates the geometry did not work. In particular, the algorithm was not able to generate the geometry of the slabs so that their volume turned out to be null as well as their emissions. The eventual solution was chosen among the others without considering the bugs. In order to have only admissible solutions it was necessary to reduce the range of variability of the points' coordinates and guarantee the generation of the slabs' surfaces. Among all of the proposed solution, a sample of 9 models was selected and only the best of them was chosen for being compared to the base case. The design of this solution could be described by the sequence reported on Figure 56. The initial trasformation change the concept from the box shape to the deformed box shape and then into the final optimized layout. Anyway, as revealed on the Method section, this algorithm did not permit to reach the improvement of the original model because of its shell, too influenced by the initial box-shape. In this part of the work the LCA calculation was not particularly reliable but it was useful for making a comparison among the concepts. Thus, the outcomes were compared considering mainly the SR and it was observed that there were no model able to improve the previous configurations. It was due to the presence of shaded part on the envelope caused by its form. The consequent SR turned out to be reduced despite of the increment of the façades' area. Anyway, the selfshading was necessary for increasing the roof's extension, improving theorically the exposure. The Table 27 shows the results of the SR evaluation for the three model introduced above: box-shape, deformed box-shape and optimized model. Both the weather files of Oslo and Perugia were employed. During this part of optimization the gap between the SR caught by the shell in Oslo and the one caught in Perugia was reduced from a 30.0 % to a 24.0 %. It highlights that the same shape's improvement does not guarantee the same betterment on each latitude. In particular, the envelope planned in this way did not permit to reach a better configuration in every case. It decreased the SR caught with a different magnitude so that the gap between the two latitude turned out to be reduced. Thus, it was necessary to develop a specific optimized shell for each considered latitude in order to evaluate the impact of the process. As shown on the Table 27 the model in Osle achieves a higher value of SR, it is 195 960 kWh/year against the 193 885 kWh/year, with an increment of the 1.1 %. Anyway, it was due to the higher extension of the envelope, as previously introduced, which change from 338.0 m^2 to 386.0 m^2 (14.2 %). It was confirmed also by observing the SR average. The base case presented a value of 568.0 kWh/m^2 year while the final model had a value of 542.0 kWh/m^2 year decreased by 4.6 %. In conclusion, it was preferred to change the approach to the shape's generation, modifying the algorithm employed in order to reduce the selfshaded parts.

5.1.3 Stage 5: complete optimization

5.1.3.1 Solar radiation and Life Cycle Assessment

In this stage of the optimization process, the solar radiation analysis was coupled with the assessment of the embodied emissions. The employment of a more powerful evolutionary solver as Octopus permits to develop several configurations with an improved value of SR caught and a reduced value of E_e. Otherwise, employing Galapagos, it could be optimized just one fitness for each time as explained on the specific tools' review. The high quantity of algorithm's variables

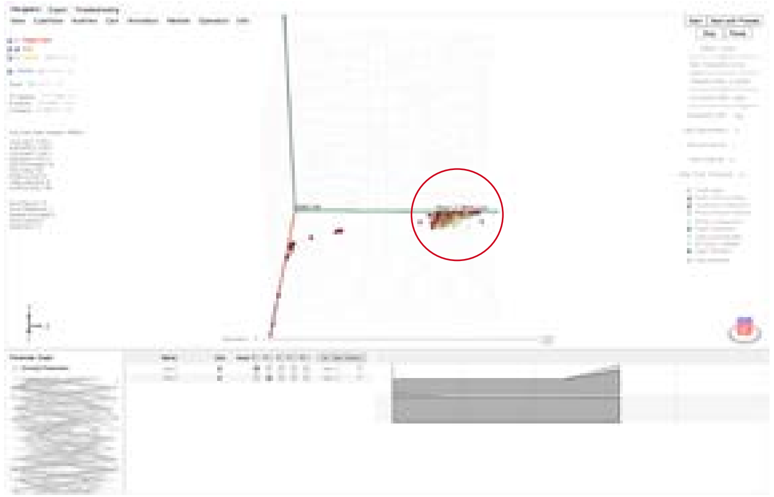


Table 58 Octopus interface and solutions evalauted during the optimization.

		box shape		deformed box		octopus output	
weather file		Oslo	Perugia	Oslo	Perugia	Oslo	Perugia
roof	*kWh/year*	83 210	119 095	63 114	89 827	85 485	106 136
outer wall	*kWh/year*	94 414	110 837	82 161	100 458	66 362	102 407
windows	*kWh/year*	18 261	21 902	34 162	43 481	44 113	35 739
total SR	*kWh/year*	193 885	251 834	179 437	233 766	195 960	244 282
SR average	*kWh/m² year*	568	737	584	737	542	743

* the partial solar radiation is refered to two contiguous façades. In this case it has been considered the façade 1 and the façade 4.

Table 27 Analyses of SR developed with DIVA for GH on the optimized models.

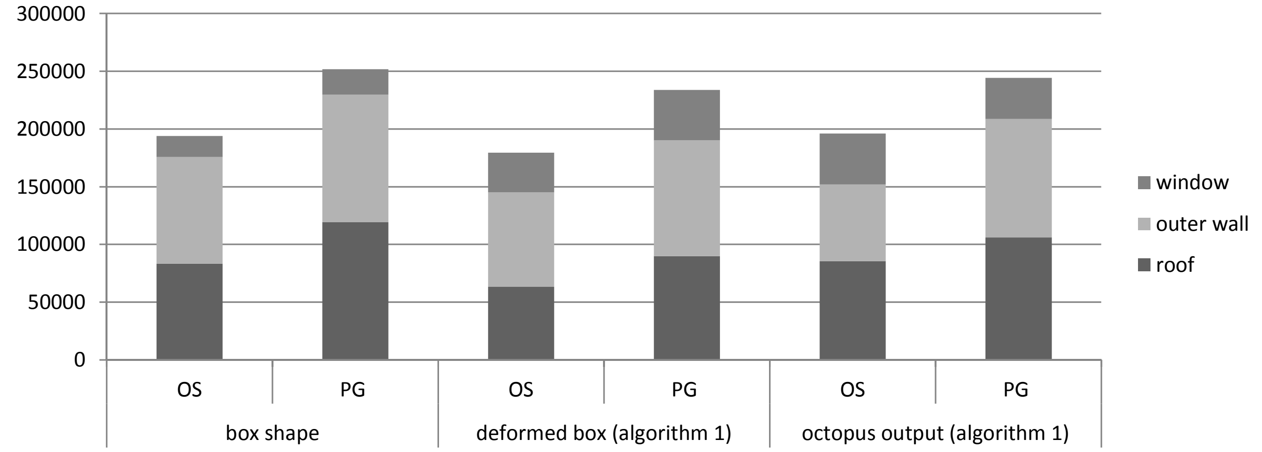


Figure 59 The graph shows the value reported on the table above about SR.

ACTIVE APPROACH

which should be managed by the solver in addition to the number of analyses required led to the employment of Ladybug instead of DIVA for GH. The first turned out to be more rapid during the evaluations so that it can be considered perfect for developing a series of continuous assessments as it happens during the problem solving. In fact, Octopus analyses start from the random combination of some genes in order to find the genomes with more possibility of being adapt for solving the problem, which is introduced into the process as fitness. There are not many differences between the considerations about the SR done during the Active Approach's section and the ones of the Passive Approach's section, except the tool used for finding the best configuration and the approach to the building's shape as explained on the following paragraph. In the end, the improvement of the SR achieved through the change of shape should be understood as a way for achieving a betterment of the PV production and not for guaranteeing the enhancement of the passive strategies.

5.1.3.2 Algorithm and Octopus optimization

This second approach to the creation of a generative algorithm that permits to find a series of improved configurations began from the observation of the previous outputs focusing on the solar radiation caught by their envelopes. Those considerations are summarized on the Figure 60 and are related to the façades, the roof and the building footprint. Each of them highlights a limit of the first algorithm and explains why the previous solutions were not able to reach an improved configuration. The shape of the façades designed by Octopus turn out to be concave and self shaded. It led to a reduction of the potential solar radiation caught by the building. In fact, the façades which compose the previous model were not able to catch a high quantity of SR on the upper part as well as on the bottom one. The whole envelope resulted to be less irradiated. Otherwise, a convex wall guarantees a higher radiation on the upper part while the lower could be maintained as the original outer wall. Thus, the building should be divided in three parts for achieved an improved configuration: the lower should be vertical, while the one in the middle is like a connection between the wall and the roof, a sort of "sloped wall" which permits to increase the SR. The roof generated on the first stage was not really different from the original because the shape was still too influenced by the original box. In this approach, it was maintained a sloped configuration for the roof. The algorithm can modify the coordinates of the four vertexes as previously tested on the preliminary studies. Changing the roof's inclination depending on the sunpath contributes to the improvement of the building's exposure. About the dwelling's footprint, it was observed that until this moment the model was just rotated without modifying particularly its rectangular shape. It led to the definition of an algorithm where it is possible to change also the *x* and *y* coordinates of the vertexes so that the rectangle could be transformed into a trapezoid guaranteeing the advantageous shown in Figure 60. Thus, the idea behind the Grasshopper interface is the generation of a building starting easily from the variation of its vertexes' position adding also the possibility of applying the same type of transformations to a group of four points along the four edges at different *z* coordinates. The number values linked to those coordinates were managed by Octopus so that it could find the configuration with the lowest level of emissions and the highest SR caught. The same procedure was applied using the *.epw* file of Perugia, an Italian city in a Mediterranean context. It permits to compare the different optimizations and better understand how the sunpath could influence the final shapes. Furthermore, the algorithm was set as well as the previous for fixing the volume and scaling the model if it turns out to be too high or too low. The procedure explained above about the optimization of the shape is strictly influenced by the weather data employed for running Ladybug's evaluations and the Octopus optimization. The *.epw* files of both Oslo and Perugia were loaded on Ladybug's engine for developing the improvement of the original box shape in order to understand how the latitude can condition the envelope's shape. The outcoming models are completely different among them and those differences are more evident than on the first approach to the shape change. It represents an important result because it means that the evolutionary solver compared a huge cross-section of the possible configurations finding the most environmentally responsive. As previously explained the models are organized in three parts, one is represented by the roof, while the other two are the lower and the upper part of the façades. The orientation of these can be managed during the optimization and it permits to have all of the solutions found. The concepts which turn out to be characterized by the best exposures are the ones compressed toward

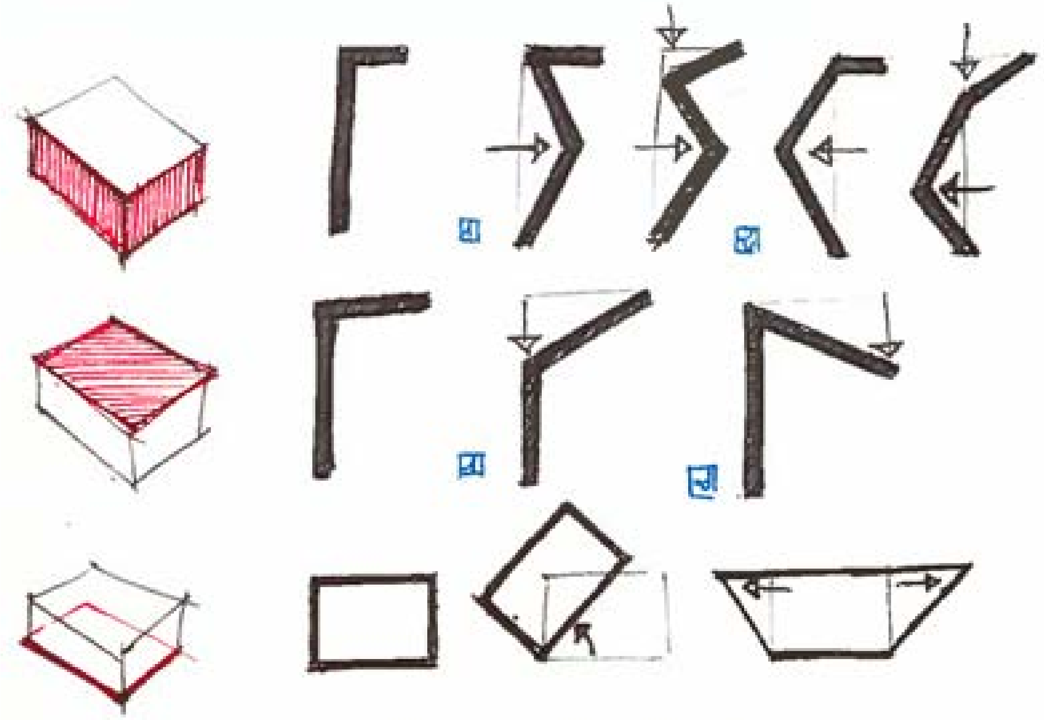


Figure 60 Consideration about the possible variation of the shape.

the ground without vertical surfaces and self shaded parts. Anyway, they were not good for being redesigned as dwelling so they were discarded. On the other hand, the concepts which guarantee a perfect compromise between SR and LCA are well designed, even if they need to be modified for being a house. The outcomes are summarized in Figure 64 and they represent just a little part of the thousands configurations analyzed by Octopus. The one selected for being developed during the next stage is characterized by pointe extremities and a variation of slopes' tilt angle. In fact, the upper part of the southern façade is tilted by approximately 50°, while the roof's tilt angle is 30°. It is quite interesting to compare this configuration with the one developed for Perugia's weather file. In that case, the two tilt angles are inverted because of the higher sunpath. In conclusion, this stage of the process ends with the choice of a model among the solutions proposed by Octopus. That shape will be redesigned as dwelling on the following paragraph.

The consequent considerations to the analysis of the previous approaches to shape change led to the definition of a new strategy which was applied in this part of the thesis. The optimization with Octopus was done using both the weather files of Oslo and Perugia in order to have two different outcomes and discuss about the influence of the latitude on them. The new algorithm for generating the new building's shell was initially coupled with the *.epw* file of Oslo and set in order to locate the best group of solutions near the origin of the plane. The Figure 62 shows the distribution of the genomes proposed by the tool: its regularity is due to the fixing of the bag previously noticed on the Stage 4. The graph shows a sort of hyperbola which describes the interaction between the E_e and the SR. Actually, the SR was not evaluated as the quantity of kWh/year absorbed by the envelope but as its mathematical inverse. The marked genomes are the ones chosen as solutions and taken into account for becoming the base for the next step on the evolutionary lineage. The diagram reported in Figure 63 summarize the values of E_e and SR for the selected models. The concept considered the most adapt is the number 2 and its shape is reported on Figure 61. It was not the model with the highest SR caught and probably not even the one with the lowest carbon emissions. It represented the most interesting for working on and the most environmentally responsive form. It permitted to catch 234 434 kWh/year instead of the original 193 885 kWh/year with an increment of the 20.9 %. Otherwise, the best configuration among the 9 selected could permit to catch approximately 336 000 kWh/year but it was not a possiblegeometry, just a theorical solution. It represented an interesting outcome but it must be taken into account that this increment is partially guaranteed by the better exposure and partly by the larger extension of the shell's surface. In fact, it grew from 297.0 m² to 444.0 m², with a variation of the 49.5 % of the catching surface. It was confirmed also by the SR average which turned out to be reduced from 568.0 kWh/m² year to 542.0 kWh/m² year with a variation of - 4.6 %. It is not so significant but it can be useful for better understanding the influence of the components' features on the results. In fact, analyzing the SR caught by the roof, it grew from 83 210 kWh/year to 111 806 kWh/year with a variation of 34.4 %, although the increment of the surface is just 13.7 %. On the other hand, the remaining building's elements were able to guarantee an improvement of the 10.8 % increasing their extension by approximately 66.3 %. It reduced significantly the average. About the emissions, they must be considered just as a value for doing a comparison because they are going to be modified on the next stage. The model chosen was able to reach a value of carbon emissions of 92 064 $kgCO_{2eq}$ which turned out to be higher than the base case's one even if it was necessary for improving the envelope's performance. In conclusion, the second model was considered as the most preferable and developed again on the next stage of the process. On the next step, it will be considered a more correct calculation of E_e, an eventual variation about SR and

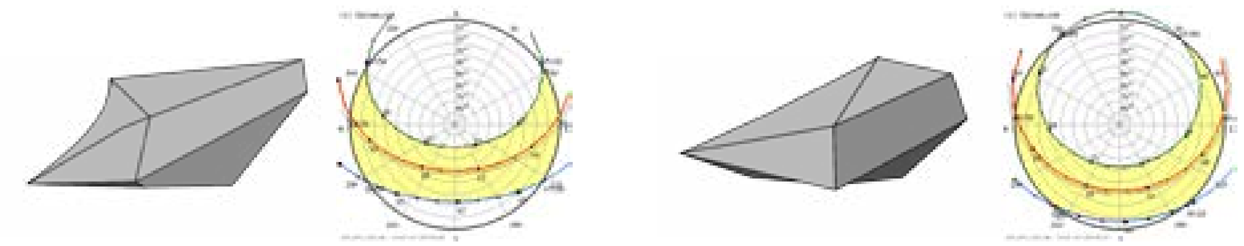


Table 61 Optmized shape for Mediterranean and Nordic latitude with respective sunpath.

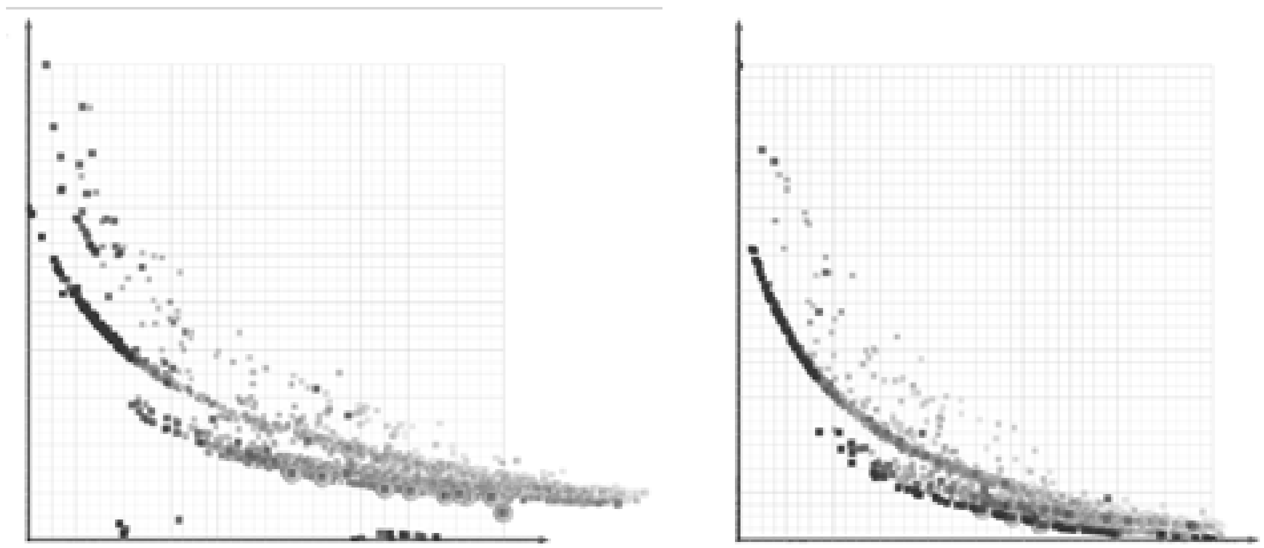
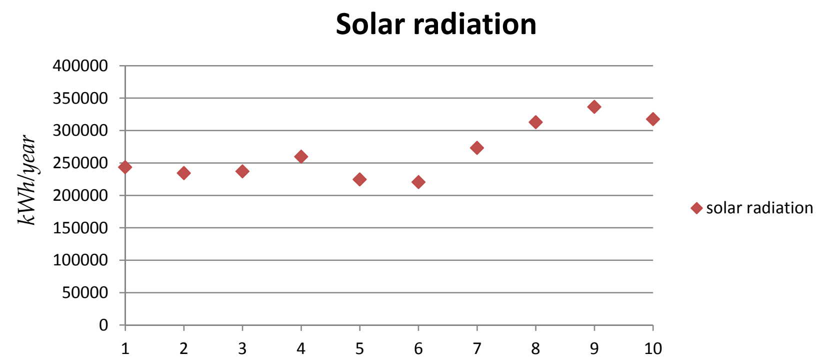


Figure 62 Trend of the genomes on Octopus interface.



octopus output	SR	E_e
	kWh/year	*$kgCO_{2eq}$*
output 1	243 282	92 814
output 2	234 434	92 064
output 3	237 087	93 782
output 4	259 656	96 168
output 5	224 479	91 441
output 6	220 384	92 041
output 7	237 201	104 355
output 8	312 632	106 067
output 9	336 600	108 947
output 10	317 430	127 998

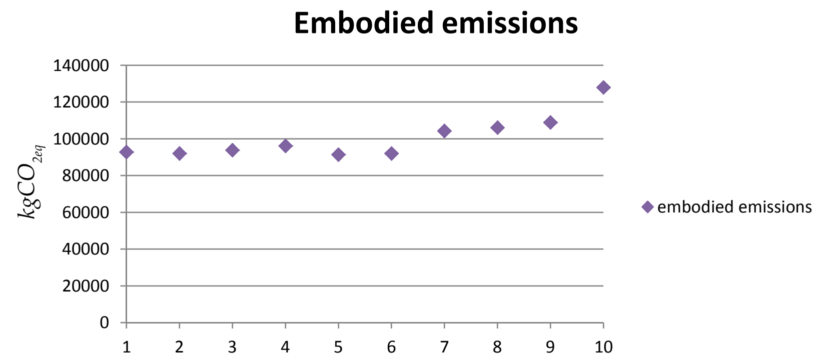


Figure 63 Solar radiation and embodied emission of the optimized models.

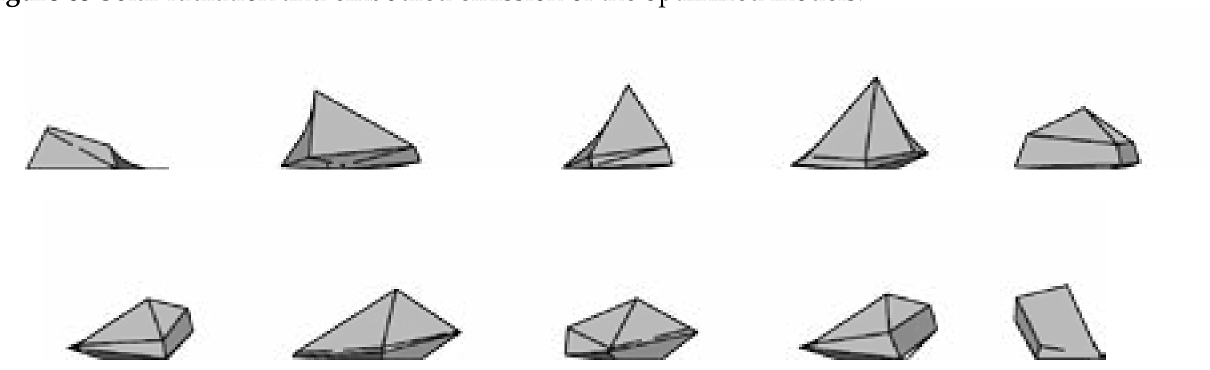


Table 64 Elevation of the optimized models.

the introduction of E_o and DF. The same procedure was applied employing the *.epw* file of Perugia instead of Oslo. The resulting concept turns out to be quite different because of the different sun-path which characterizes those latitude. The two different sunpaths are shown on Figure 61. The main difference was limited to the tilt angle of the roof and the upper part of the façades. In fact, the solver chose two different tilt angles for the façades and the roof for Oslo. Otherwise, in Perugia they were approximately the same in terms of inclination (55°). The concept was able to absorb 339 000 kWh/year instead of the 251 834 kWh/year of the base case model evaluated in a Mediterranean context. The increment was 34.6 % and differently from Oslo, in this case it was guaranteed mainly by the improvement of the façades. Also on the Italian configuration, the area turned out to be significantly increased growing from 297.0 m² to 495.0 m² with a variation of 66.7 %. On the other hand, the embodied emission related to this concept were estimated as 94 439 $kgCO_{2eq}$, not so different from the Oslo improved model. In conclusion, the solver tried to optimize the base case model by working on a better exposure and an increment of the envelope's area which results in a lot of case compressed toward the ground as much as possible in order to reduce the emissions considered as fitness. Thus, in this stage the evaluation and the interpretation of results made by the planner was particularly important in order to choose the best solution and define the features which must be redesigned during the next step.

5.1.4 Stage 6: final active model

5.1.4.1 Model description

The last stage of the optimization process analyzed on this master thesis is reported in this paragraph. Until now, it was defined an adequate shape for the shell that allows to increase the SR caught without losing the improvements reached during the PA's section. As previously introduced, one of the models evaluated by Octopus was chosen for being redesigned as house. On the final building, this optimized shape was introduced as a second skin integrated with another volume which delimits the dwelling. The two elements should be characterized by different layout and the optimized shell should be partially covered by BIPV system. The resulting building turned out to be quite influenced by Nordic architecture. It is a good feedback that confirms the accuracy of the method applied and the high quality of the results. It is easy to be noticed the similarity with the Oslo Opera House and the ZEB pilot house. They influenced the model about the interaction between two volumes and the definition of the tilt angle of the surfaces. Both the architecture are planned by Snøhetta, an international group of architect based in Oslo and particularly operative in Norway. The first example is a construction composed by an inner wooden volume and an external one made from Italian Carrara marble. The two elements interact thanks to some cuts on the outer shell which permits to see the interior surfaces covered by oak. Those cuts create a large sloped plaza that invites pedestrians to walk up and enjoy the panoramic views of Oslo. Even if it is not possible to walk up on the final concept, the visual effect results really similar. The second building previously introduced is another pilot house developed and built by the Research Centre on Zero Emission Buildings in Oslo on 2014. It is a pilot project of family house that is able to produce more energy than it needs. The house has a characteristic tilt toward southeast and a sloping roof surface clad with solar panel and collectors. The Figure 65 shows how starting from this reference is possible to achieve the configuration of the final model optimized with this method. The main transformations involved the building footprint and the sloped roof. In fact, the ZEB pilot model is characterized by a rectangular footprint which turns out to be deformed into a sort of rotated trapezoid on the last concept. About the sloped roof, on the reference the tilt angle is maintained constant while on the optimized model it changes from 50° to 30°. On the other hand, the openings which permit to see the inner volume, designed with a change of slope's direction, seems based on the first example, the Opera House. Actually, another confirmation that the shape optimized with Octopus is particularly adapt for this latitude can be found on the project of the Powerhouse at Brattørkaia in Trondheim. Also this building is designed by Snøhetta, but the construction is not yet completed. It is going to be the first office building in Norway that could produce more energy than it uses. The building will have a 26 degree sloped south-facing roof to best utilize solar energy which is not so different

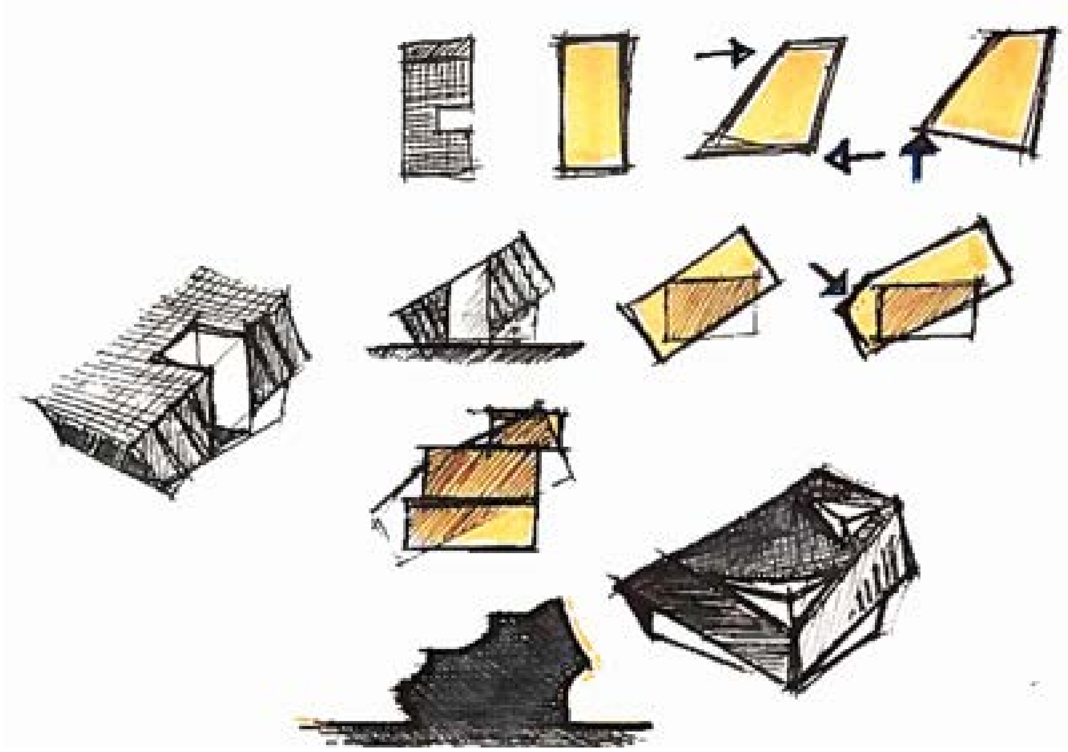


Figure 65 From the reference to the optimized model. A series of applied transformations.

Figure 66 ZEB Pilot house in Larvik designed by Snohetta.

Figure 67 Oslo Opera House designed by Snohetta.

from the 30 degree that characterized the optimized roof of the Oslo's pilot model developed on this master thesis.

5.1.4.2 Rooms' arrangement

The rooms' arrangement was considered as a consequence of the building's envelope. The change of its shell led to the modification of the inner space's organization. Some boundaries about the approach to the redesign of the model were defined. First of all, the volume has to be maintained constant through every transformation in order to generate concepts not too different. It was realized introducing the Scale component into GH's algorithm so that all the outputs from Octopus's optimization had the same features. On the other hand, the BRA was maintained as much similar as possible as well as the number and types of rooms which compose the house. The same constancy was not guaranteed for the envelope's surface. It changed causing the variations on the heat losses through the shell. Also the same number of persons who can live and occupy the building has been maintained constant, for example the four bedrooms of the base case model were proposed again on the improved concept. It is fundamental for comparing correctly the operational emissions, which depends on the occupancy, of the different houses. As on the PA, it was taken into account the location of servant and served spaces and their orientation. The arrangement was organized in three levels: all the bedrooms and a bathroom are located at the first level which turned out to be more extended than the second. The second are planned as an open space where a kitchen, a living room and a dining room are placed. The stairwell continues upper than the second level toward a sort of terrace partially covered by the external shell. This space represents a new among the building's zones. It was not considered in the base case model and it is probably one of the main elements of interaction between the two volumes that composes the construction.

5.1.4.3 Daylighting evaluation

The approach to daylighting is different from the one in the PA. On the previous approach, it was evaluated firstly the configuration with the lowest limit value of windows' surface for guaranteeing the optimal DF and then the one with the most extended possible glazed surface. In this section, it was estimated the DF for the developed configuration. No particular considerations were made about the variation of the ratio window to wall because the impact of it on the building's improvement was already analyzed on the PA. It was verified that the inner spaces would have a good daylighting without considering too small openings or just the minimum quantities. The evaluation of the DF was developed as on the PA coupling the geometric output of the generative algorithm with the Radiance engine, which is included in DIVA for GH. The workplane was set at a distance of 0.9 m from the floor's level and the weather file considered was referred only to Oslo. None comparison was made with Perugia's weather data. Anyway, for having more detailed information about the procedure applied, it could be viewed the PA's section.

5.1.4.4 Environmental analyses

The redesign of the optimized shape as a dwelling influenced the SR caught, which turned out to be modified passing from the stage 5 to the stage 6. The new shell and its optimization with Octopus permitted to have a building less compact and a catching surface more extended. Thus, the features which represented a disadvantage in terms of embodied emissions, and propably operational emissions too, turned out to be advantageous considering the SR. In fact, a larger and better exposed surface is able to absorb more heat than a more compact one. The last stage on the evolutionary lineage evaluated on this paper guaranteed an increment of the SR from 193 885 kWh/year to 273 552 kWh/year with a variation of 41.1 %. Furthermore, the outcomes highlighted an improvement of the 16.7 % in respect to the previous shape which was characterized by 234 434 kWh/year. Also in this step the increment seems to be partially due to the growth of the envelope's surface which varies from 297.0 m^2 to 504.0 m^2 and it was confirmed by the average, reduced from 568 kWh/m^2 year to 532 kWh/m^2 year. In fact, the improvement of the roof's exposure as well as the addition of the shell created shaded zones on the façades contributing to the reduction of the average. The results introduced in this paragraph are summarized on Table 28. These evaluations represented the first step toward the definition of a building integrated active system for the energy production

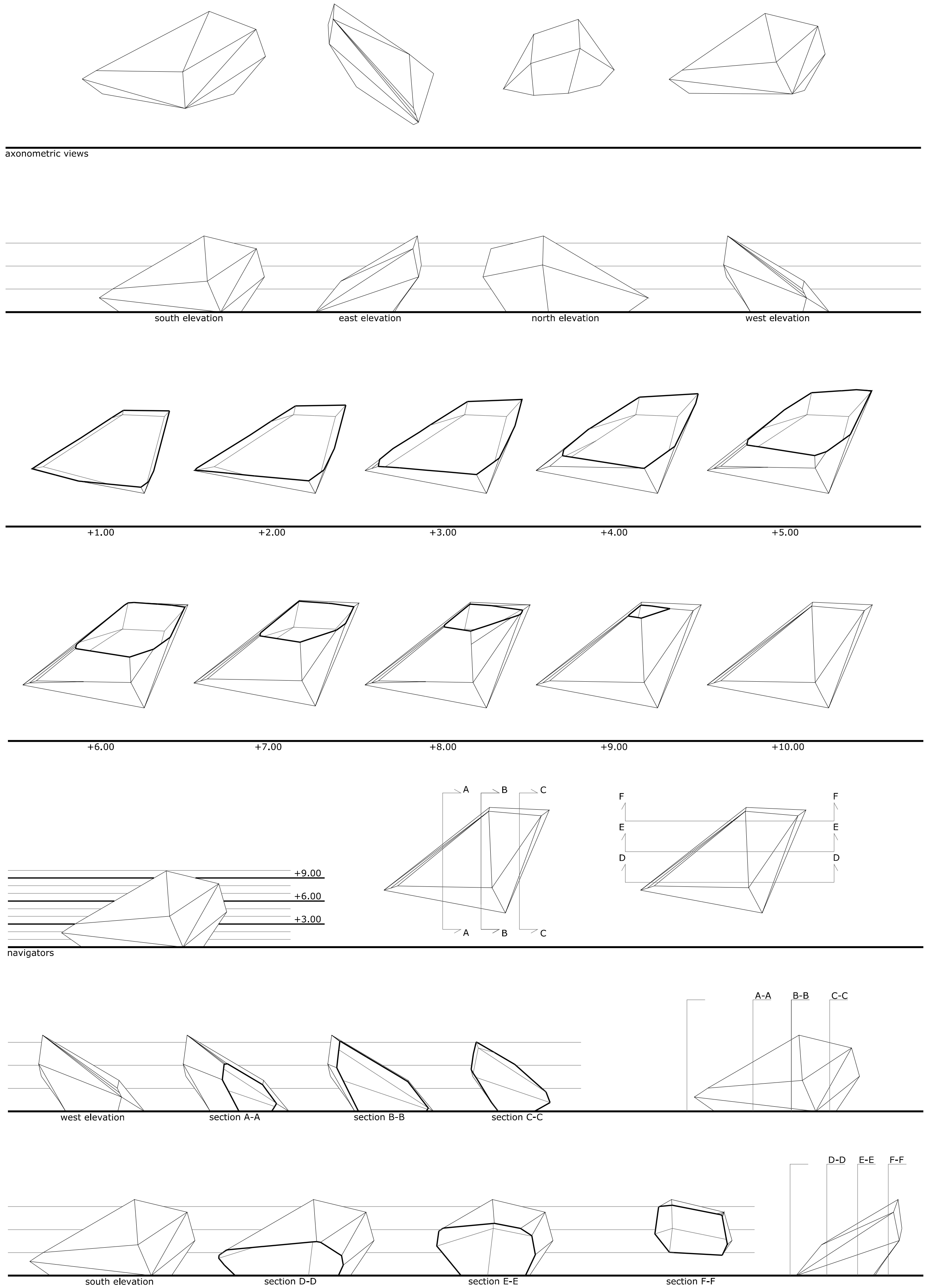


Figure 68 Optimized shape.

ACTIVE APPROACH

and the optimization of the ones already present on the envelope such as PV and solar thermal collectors. It represents the core of this stage of the process and it will be largely examined on the specific paragraph.
The windows' size and dimension were planned in order to guarantee at least the minimum DF which is approximately 2.50 %. It was not calculated the minimum extension of glazed surface because it was analyzed on the section about PA. It was not considered interesting to assess again the impact of a glazed surface on the carbon emissions. In this part, each room of the building had at least one opeining in order to allow a natural ventilation. Their size and position permitted to achieve a DF average of 10.03 %, largely over the common standards. The DF was calculated as on the previous section, the workplane was set 0.90 m hight and the grid cells have an edge of 0.10 m in order to have a detailed output. The Figure 68 shows the variation of the DF on the workplanes related to the two levels of the dwelling. The better exposure and distribution of the openings increased DF even if the windows' area turns out to be approximately the same of the base case, 40.5 m^2 on the ZEB pilot model against the 39.1 of the final one. The DF calculated on this stage and intro-

		box shape *Stage 0*		octopus output *Stage 5*		optimized model *Stage 6*	
weather file		Oslo	Perugia	Oslo	Perugia	Oslo	Perugia
roof	*kWh/year*	83 210	119 095	111 806	111 550	174 529	-
outer wall	*kWh/year*	110 675	132 739	122 628	227 456	99 023	-
total SR	*kWh/year*	193 885	251 834	234 434	339 006	273 552	-
SR average	*kWh/m² year*	568	737	542	743	532	-

* the partial solar radiation is refered to two contiguous façades. In this case it has been considered the façade 1 and the façade 4.

Table 28 Analyses of SR for the models developed during the three stages reported above.

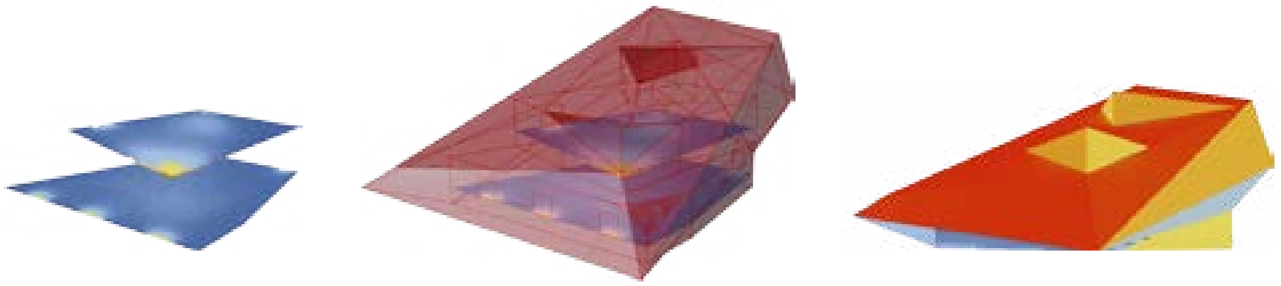
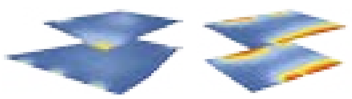


Figure 68 Environmental analyses about SR and DF.



10.03	7.52	%	**daylighting factor ***
9.97	34.75		**ratio window to wall**
21.4	40.5	*m²*	**glazed surface**
87 422	80 373		**$kgCO_{2eq}$ ****
9.11	8.37		**$kgCO_{2eq}/m^2$ year *****

* the DF is calculating considering a grid of test points 0,9 mt far from the floor.
** the $kgCO_{2eq}$ is evaluated based on a building's lifetime of 60 years.
*** the $kgCO_{2eq}/m^2$ year is estimated for a BRA of 160 square meters.

Table 29 The models genereted by Grasshopper alghorithm have been compared considering mainly daylighting factor and $kgCO_{2eq}$.

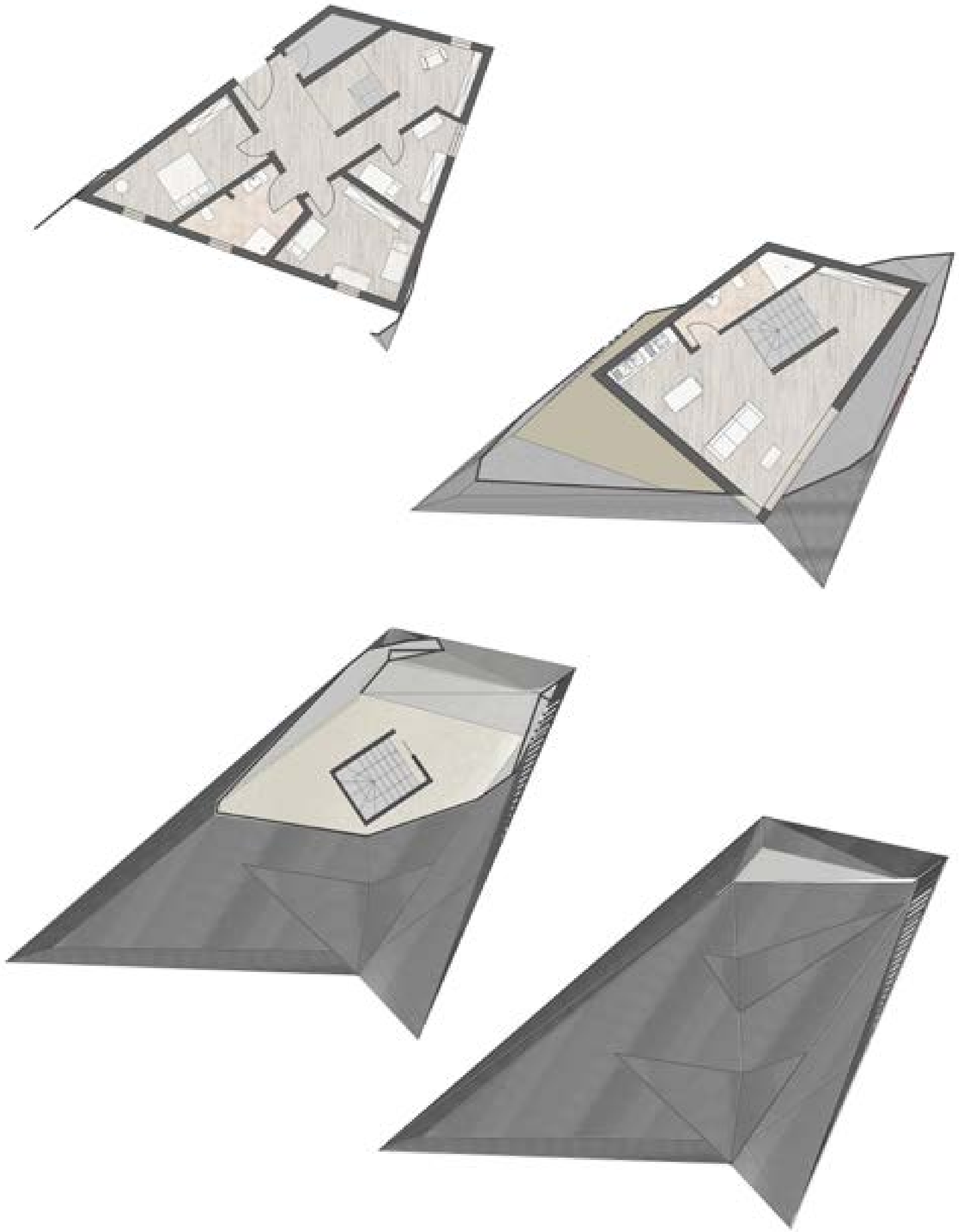


Figure 69 Stage 6: final active model.

duced above is 10.03 % while the original was 7.52 % with an improvement of the 38.6 % of it and a reduction of the 3.0% of the glazed surface. In the Table 29, it is reported the comparison between the base case and the concept developed in this stage.

5.1.4.5 Active façade

The active façade represents an innovation on the ZEB pilot project developed by the Research Centre on Zero Emission Buildings. Until now it was evaluated just the possibility of extended the PV system on the southern façade without not many calculations or assessments. In this step, it was considered the application of a BIPV system on the façades, as explained in detail on the paragraph about the PV system's improvement, and the possibility of employing different energy sources such as the algae panels. The optimization of the model considered the improvement of the SR as part of the core of this research. It led to the choice of a system for producing energy able to exploit the sun power. In addition to that, it was taken into account the possibility of installing a technology which can introduce the dynamism in façade without incrementing the energy demand. The solution evaluated is the application of algae panels for creating a "green façade". The technology and the case studies are introduced on the specific section. Anyway, the algae panels allow to produce heat and biomass, thus electricity. They could be used instead of the solar thermal panel and coupled with the BIPV system for producing electricity. Furthermore, the algae absorb CO_2 for producing biomass during the photosynthesis and contribute in this way to the emission balance with a reduction of the $kgCO_{2\,eq}/m^2$BRA year calculated. The consideration about the employment of algae panel and their eventual contribution are reported on the specific paragraph.

5.1.4.6 PV system

The change of shape is the first step toward the improvement of the active strategies such as the increment of the PV production. Increasing the total SR caught by the envelope and placing the cells with an optimal tilt angle guarantee a higher efficiency of the elements and a better energy production. Obviously, the employment of more panels influences also the embodied emissions of the dwelling. It is necessary to evaluate this variation during the development of the PV system. Thus, the betterment of the efficiency was realized before working on the extension of the PV surface placed over the shell. Once the geometry was defined, the area available for this expansion has been evaluated and it is reported on a graph. On Figure 75, it can be seen the variation of emission balance so that the achievement of the ZEB - OM level could be easily identified. The PV system proposed for being applied on those models is the same used on the base case model so that it is more evident the influence on the total production of a well exposed shell with a BIPV system. In fact, the focus of this research is exactly the envelope of the building and how its transformations could condition some building's features such as carbon emission, energy demand, solar radiation and daylighting. The assessment of the energy production was developed considering the cells' efficiency and the SR incident. Multiplying these two factors it has been found the kWh/year generated by the system. For understanding which is the consequent value of emissions expressed in terms of $kgCO_{2eq}/m^2$BRA year, it was included another factor that takes into account the ecological footprint of the electricity production. The electricity which is produced in a *green way* in situ permits to reduce the house's energy demand toward the network as well as the emissions linked to this process. The factor is strictly influenced by the context, the country and the quality level of national energy production. In a state like Norway where more than 90 % of the electricity is *green* and produced with hydroelectric station, the electricity mix turns out to be quite small if compared to the one characteristic of other nation. As reported on Houlihan Wiberg's research [55] about energy and buildings, the choice of the symmetric emission factor of 0.132 $kgCO_{2eq}$/kWh was applied in agreement with the ZEB Centre guidelines. The same factor was employed to calculate the emissions from the electricity used for operation as well as the calculation of the emissions from the electricity produced by PV.

5.1.4.7 Algae panel

The buildings consumption contributes significantly in the total demand of energy. In Netherland, for example, the value for buildings' consumption is approximately 30 % on the basis of the Fong

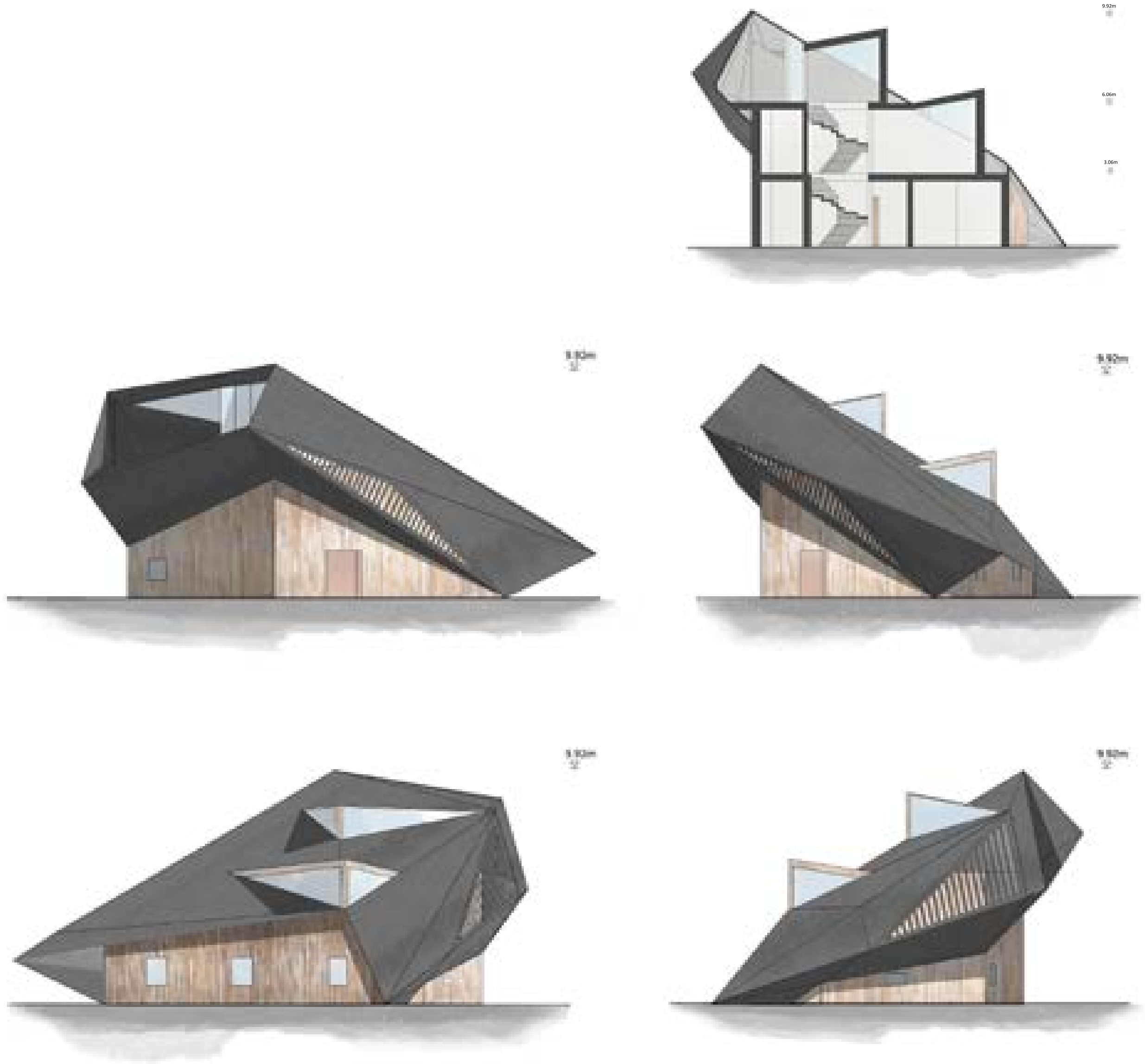


Figure 70 Elevations and section of the model developed on Stage 6.

Figure 71 Passive office project in Trondheim developed by ZEB Centre and Snohetta.

Qiu's research [66]. Thus, it starts to be fundamental reducing this percentage by applying different strategies such as the improvement of the energy generated by the building itself. Nowadays the most popular solutions for energy demand are wind turbines and photovoltaic panels, but on this project it was considered also the algae panels. It is due the necessity of both producing energy and reducing the CO_2 emissions of materials employed during their life cycle. In this terms the algae panels could represent an adequate solution. The algae permits to achieve several benefits such as the production of biomass, later converted into electricity or sold, the heat generation and the mitigation of the carbon emissions thanks to their photosynthesis process. Anyway, this is an example of really young technology with few applications on buildings and not many tests if compared to other systems as PV. The panels are normally filled with microalgae, which are unicellular primitive organisms which cannot be seen with naked eye. They are microscopic and they are able to grow up quickly into water with a lot of nutrition. The water changes its colour in green or blue, orange or brown as explained on the research of Fong Qiu [66] about the application of this technology to the in situ energy production. It depends on the velocity of the reproductive process that allows the façade to change its colour becoming a sort of dynamic façade, responsive to the sun. It is also quite interesting for the design and considering an aesthetic point of view. Probably, the first building that integrates its envelope with a bioreactor façades is the BIQ House, an Arup's constraction showcased at Building Exhibitions in Hamburg. In the southern façades 129 Solarleaf modules were used with microalgae, covering a surface of 200 m². In this case, Solarleaf technology employed flat panels instead of tubolar module. Algae could be organized as pipe or panel, even if it was demonstrated that the performances of the second are better than the first. Obviously, the energy production depends on several factors such as sunlight, strain of algae, type of cultivation and type of energy produced. The efficiency and the data evaluated on the different tests change substantially depending on the latitude. It is not possible to certainly predict how much the amount of energy produced will be. The module have 1.56 m² of glazed surface, with 0.60 m of width and 2.60 m of length. It is composed by four monolithic glasses supported by steel sub-frame. In the bottom part of this structure there are pumps and valves for the operation. Furthermore, there is a cavity between two layer of glass for medium circulation 18 mm deep filled with water and algae. When the valve is open the compressed air is introduced and it mixes the nutrient and the carbon, generating in addition to that a turbulence that cleans the glass. The biomass is produced by a chemical process, the photosynthesis, meanwhile the heat is produced by solar thermal effects. The sunrays hit the glazed surface warming up the water inside. The heat and the biomass are transported on a closer loop system toward the plant room, where the heat is removed from the culture through an heat exchanger. It is possible to use this energy directly or stored. The biomass is extracted by a separator and then it can be used for the electricity production, stored or sold. For evaluations and considerations about the modules' efficiency, it has been used as main reference the study developed in Munich. As shown on the Figure 72, considering a SR of 1150 kWh/m² year, the panel shoud be able to absorb approximately 550 kWh/m² year, the other 50 % loss is due to orientation, exposure and reflection. This amount of radiation is employed for activating the phtosynthesis and being trasformed in heat and biomass. The first is 220 kWh/m² year (40 %) while the second is 50 kWh/m² year (8 - 10 %). From the last is possible to obtain 40 kWh/m² year as biomass which is approximately the 80 % of the original biomass. Otherwise, the Arup's pilot project in Hamburg, which employs bioreactor façade in a different latitude from Munich, is expected to produce biomass for 30 kWh/m² year and heat energy for 150 kWh/m² year with a reduction of total CO_2 emission of 2.2 tons per year. Yet, also GrowEnergy in San Diego produced a flat panels called Verde and Hydra with a similar technology and properties. Using this kind of technology could turn out to be too expansive, so it is important to improve the efficiency and reduce the cost of this. It is what many experimentations are already doing. Cesare Griffa Architecture Lab is working toward this direction, his team has studied a plastic and sustainable envelope in polymer for algae, which reduces probably the lifespan if compared to glass, guaranteeing an easier procedure of installation in each surface and a structure surely lighter than the Solarleaf panel's one.

5.1.4.8 Emission balance

The emission balance considered in this research was composed by three main components: the em-

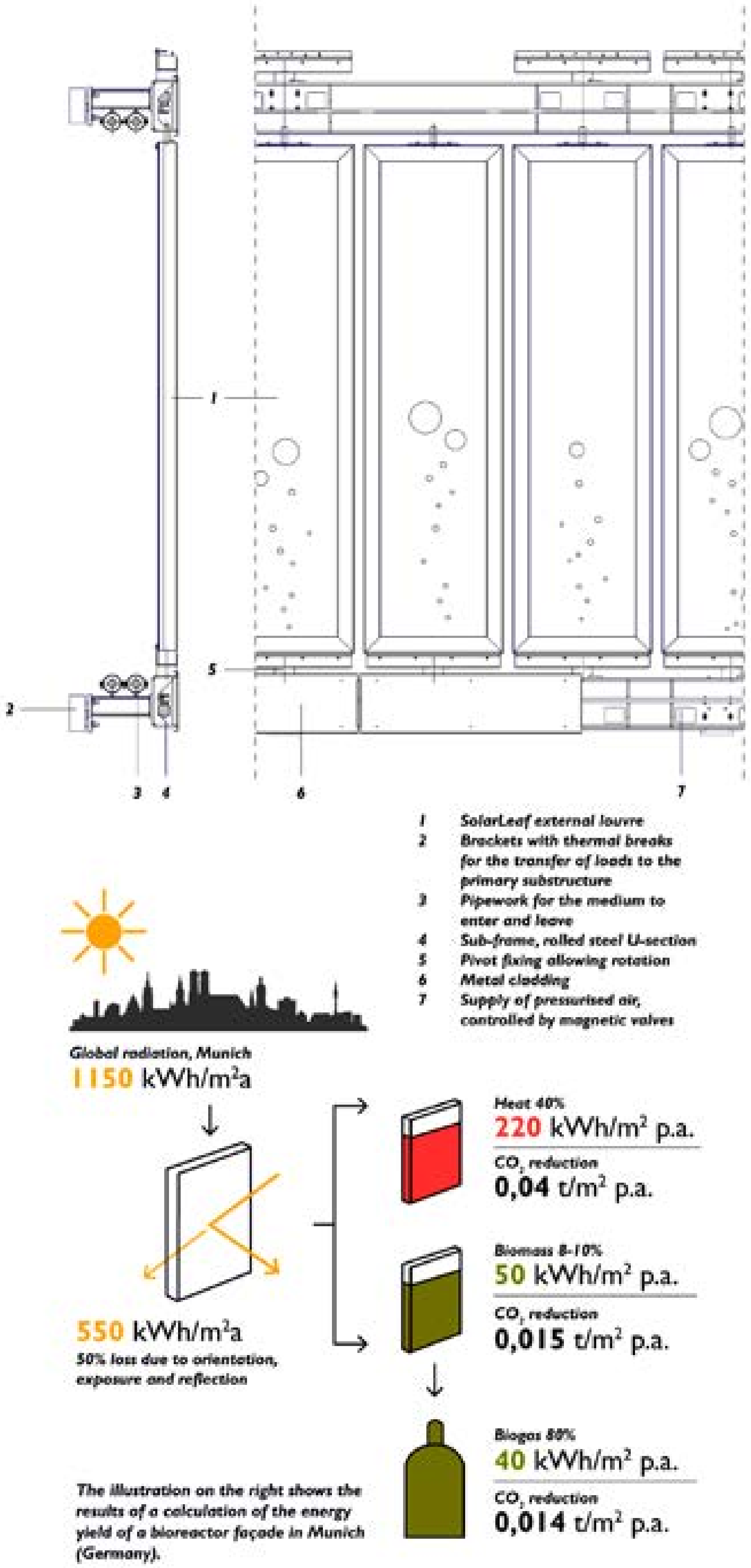
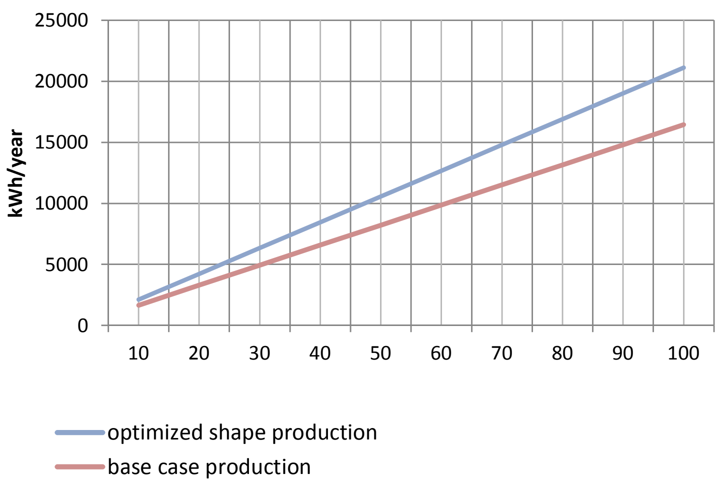


Figure 72 Algae panel efficiency.

bodied emissions, the operational emissions and the PV production. Each contribution was calculated considering the boundaries and the functional unit introduced on the section about Method. The building was not particularly different from the original base case except for the dimensions and the form. In fact, it was decided to maintain a timber structure coupled with a shell which works as underlayer for the BIPV system. In particular, the shell was organized with a sequence of layers similar to the roof except for the insulation which was not requested on it. Furthermore, its load bearing structure was not composed by wood truss beam but it was preferred a structure made from stell. This element is foundamental for improving the building exposure without increasing the dwelling's volume. The embodied emissions' level related to this model and reported on Table 30 were 87 422 $kgCO_{2eq}$ (9.11 $kgCO_{2eq}/m^2BRA$ year). It turned out to be higher than the concepts developed before. The variation was due to the increment of the outer walls' area, thus the lack of compactness of the building, which influenced also the operational emissions as later explained. The compactness, which is the ratio area to volume, on this configuration was approximately 0.92 m^2/m^3 against the 0.77 m^2/m^3 of the base case. There was a variation of the compactness of 19.0 % consequent to the increment of outer walls' area from 386 m^2 to 460 m^2. Otherwise, the volume did not change significantly. The employment of a shell increased the E_e by approximately 10 000 $kgCO_{2eq}$ (1.04 $kgCO_{2eq}/m^2BRA$ year). It means that it influenced the calculation causing a growth of more than the 10.0 %. In addition to that, working with a so high value of glazed area did not permit to reach a level of embodied emissions as low as the one calculated on the Stage 3 even if the impact is not too significant. In fact, considering just 12.0 m^2 of windows' surface it is possible to reach a value of E_e of 86 583 $kgCO_{2eq}$ (9.01 $kgCO_{2eq}/m^2BRA$ year), not particularly different from the 87 422 $kgCO_{2eq}$ (9.11 $kgCO_{2eq}/m^2BRA$ year) of the glazed model. In conclusion, this model cannot be considered a good evolution of the previous one taking into account only this part of the LCA calculation. But the emission balance is composed also by the operational emissions and, above all, the PV production which was the main properties probably optimized in this section. The first was evaluated using Design Builder for interfacing with Energy Plus engine. The concept was modeled

structural element	**unit**	***base case***	***optimized model***
Roof		6 103	6 630
Outer walls		16 233	11 708
Slab	*$kgCO_{2eq}$*	2 315	1 911
Shell		-	10 264
PV		27 490	27 490
Other		28 232	26 506
total embodied emissions	*$kgCO_{2eq}$*	80 373	87 422
	$kgCO_{2eq}/m^2BRA$ year	8.37	9.11

Table 30 Emissions from the base case and the model optimized on Stage 6 with the same amount of PV cells.



area	***Energy produced***	
m^2	*kWh/year*	
10	2 112	1 643
20	4 224	3 286
30	6 336	4 930
40	8 448	6 573
50	10 559	8 216
60	12 671	9 859
70	14 783	11 502
80	16 895	13 146
90	19 007	14 789
100	21 119	16 432
	optimized	***base case***

Table 31 Trend of the PV production on the two different models.

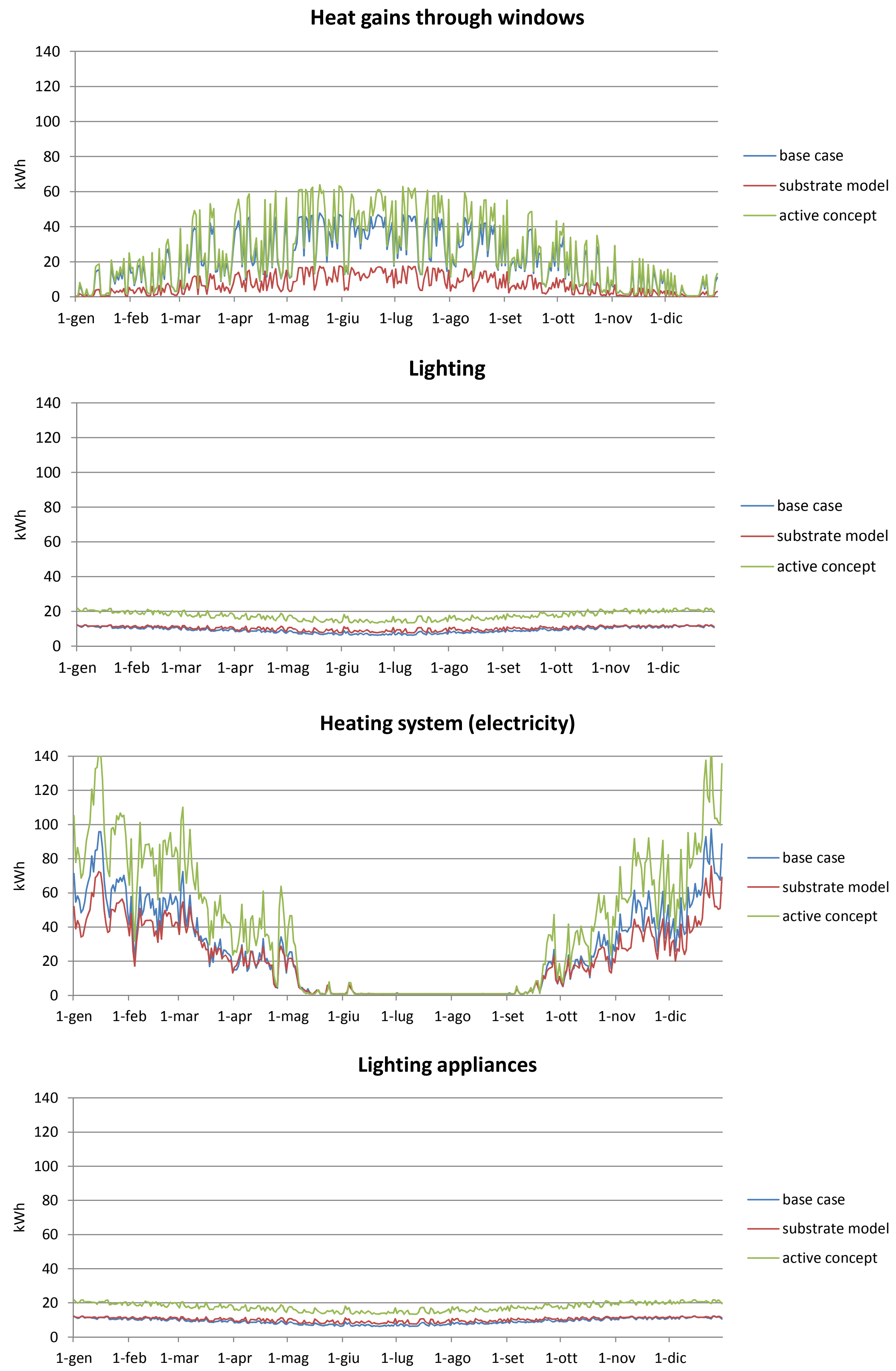


Figure 73 Desing Builder output about energy demand and envelope's efficiency.

without considering the shell, but only the lived volume. In this stage, it was not possible to reduce again the operational emissions as did on the PA. In fact, they turned out to be increased from 5.00 $kgCO_{2eq}$/m²BRA year to 9.70 $kgCO_{2eq}$/m²BRA year. It depends on several factors such as the openings' arrangement and the building's compactness. While in the PA it was developed a model with the minimum extension of glazed surfaces, the dwelling defined in this section is characterized by large windows as suggested by the increased DF. Thus, both the heat gains and the heat losses through the windows resulted to be more significant than on the other models. It led to the increment of the energy demand for heating the house even if the volume is maintained constant. Moreover, the compactness of the dwelling is different from the one which characterized the PA as previously explained. It represented a disadvantage in terms of operational emissions because the surfaces which can disperse the inner heat toward the outer environment turned out to be more extended. The graphs reported in Figure 73 show the distribution of the heat gains through the windows during the year and the heating system electricity demand calculated with Design Builder. Although the openings' size was increased, the energy demand for lighting appliances turns out to be higher than the one calculated for the other cases. It is due to the different shape of the new model. Thus, until this moment the emission balance showed that both the E_e and the E_o resulted higher after the process of optimization. In particular, their sum is 18.81 $kgCO_{2eq}$/m²BRA year against the 12.28 $kgCO_{2eq}$/m²BRA year achieved on the concept where the passive strategies were improved. The variation was more than the 50.0 % and it must be balanced with an increment of the PV efficency for reaching the ZEB - OM ambition level. Actually, a betterment of the active system's energy production was achieved by planning a BIPV system well exposed, instead of the original PV system. The better exposure permitted to increase the PV contribution on the emission balance from 9.20 $kgCO_{2eq}$/m²BRA year to 11.50 $kgCO_{2eq}$/m²BRA year. It was an enhancement of 25.0 % without increasing the PV surface. In fact, the original 69.0 m² of PV were partially oriented toward North losing so approximately the 6.0 % of the efficiency. Placing all the cells Southward with a tilt agle which varies from 30° to 50° permits to maintain the highest efficiency, 20.4 %, on the whole surface. On the Table 29 is shown the trend of the PV production depending on the area. The gap between the PV production of the optimized shape and the one of the original box grows with the increment of the area. In conclusion, the final emission balance reported on Figure 74 highlighted a mismatch of - 7.27 $kgCO_{2eq}$/m²BRA year because the PV system is not able to equalize the sum of E_e and E_o. The ZEB - OM ambition level cannot be achieved without improving again the active systems' contribution, especially considering that there is still a huge part of surfaces available.

5.1.4.9 Active improved scenarios

In this part, several possible scenarios were evaluated in order to increase the production of energy and reduce consequently the carbon emissions. In this way, it should be possible reaching the ZEB - OM ambition level as previously revealed on the active development of the substrate passive model. The integration of the existent PV on the flat roof with a BIPV on the southern façades allowed to balance the carbon emissions of the concept developed on Stage 5. Otherwise, the shape change permits to sobstitute completely the PV, which did not have a great efficiency, with the BIPV system. On the first active scenarios, it was considered just the possibility of improving the CO_2 reduction by adding new solar cells on the shell. Actually, not the whole shell was considered adapt for being covered by panels, but just the slopes with the best exposure. Thus, the available surface for BIPV on the shell is 173.0 m². On the previous active concept only 69.0 m² of these were covered with solar cells. The variation of the cells' number influences the embodied emissions related to the model. The trends of the E_e and the BIPV production as a function of the percentuage of available surface exploited is reported on Table 32. Furthermore, the graph in Figure 75 shows the variation of the whole emission balance depending on the same percentuage introduced above. It highlights how it should be necessary to cover at least the 74.0 % of the available area in order to reach the ZEB - OM level. In particular, a surface of 138.4 m² guarantees a CO_2 reduction of 23.10 $kgCO_{2eq}$/m²BRA year against the 9.20 $kgCO_{2eq}$/m²BRA year of the base case model. The reduction turned out to be more than doubled so that it is able to balance the increment of emissions caused by both the variation of BIPV area and the modification of the shape. The E_e varies from 6.24 $kgCO_{2eq}$/m²BRA year, when the BIPV is not present, to 11.98 $kgCO_{2eq}$/m²BRA year which included a system 138.4 m² extended. This

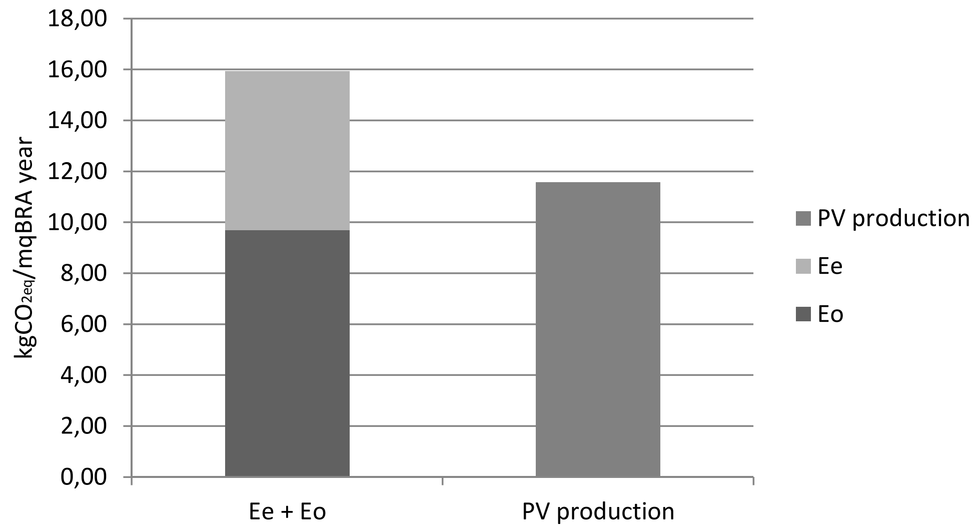


Figure 74 Emission balance of the model developed at Stage 6 without increasing the PV extension.

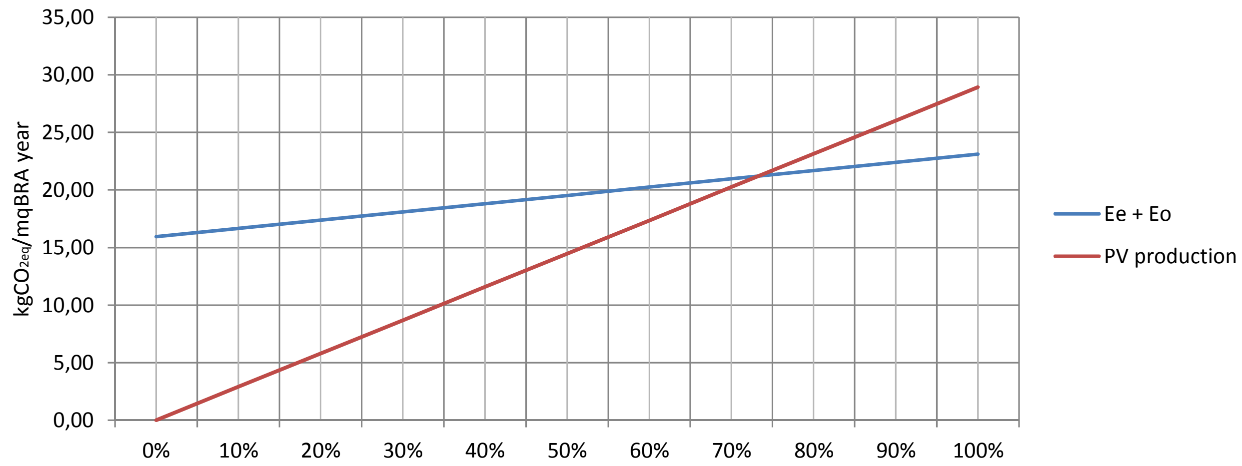


Figure 75 Variation of the emission balance depending on the percentuage of available surface covered by PV.

surface available	*m²*						173.0					
PV surface	*%*	0.0	10.0	20.0	30.0	40.0	50.0	60.0	70.0	80.0	90.0	100.0
	m²	0.0	17.3	34.6	51.9	69.2	86.5	103.8	121.1	138.4	155.7	173.0
*PV production**		0.0	2.9	5.8	8.7	11.6	14.5	17.4	20.2	23.1	26.0	28.9
*E_e**		6.2	7.0	7.7	8.4	9.1	9.8	10.6	11.3	12.0	12.7	13.4
*E_o**							9.7					
*E_e+ E_o**		15.9	16.7	17.4	18.1	18.9	19.5	20.3	21.0	21.7	22.4	23.1
*balance**		- 15.9	- 13.8	- 11.6	- 9.4	- 7.2	- 5.0	- 2.9	- 0.7	1.5	3.6	5.8

* the unit considered is $kgCO_{2eq}$/m² year which is evaluated based on a building's lifetime of 60 years and a BRA of 160 square meters.

Table 32 Variation of the emission balance depending on the percentuage of available surface covered by PV.

configuration with a 80.0 % of the available surface covered by solar cells permitted to achieve the ZEB - OM level with a positive mismatch of 1.46 $kgCO_{2eq}/m^2BRA$ year. The extreme solution with the whole envelope covered by BIPV system guaranteed a reduction of 28.90 $kgCO_{2eq}/m^2BRA$ year, an embodied emissions' quantity of 13.42 $kgCO_{2eq}/m^2BRA$ year and a consequent mismatch of 5.81 $kgCO_{2eq}/m^2BRA$ year. This was the maximum of the potentiality of this model and this approach in particular. A different strategy for reaching the ambition level required is represented by the option described on the following lines. It was evaluated the possibility of integrating the BIPV with the algae's technology. The algae panels can guarantee several advantagies to the dwelling and its emission balance. In fact, they are able to produce heat thanks to an heat exchanger which absorbs heat from the water inside the glazed panels. Moreover, they can generate electricity through their biomass and absorb the CO_2 from the environment like a green roof. Unfortunately, there are not still a lot of data about their application to building's façades. Nevertheless, it was observed that this technology is more efficient for producing heat than for generating electricity. The configuration proposed employed the algae panels in place of the solar thermal collectors. Even if they have a lower efficiency, 27.9 % against the 60.0 %, they were able to reduce the carbon emissions. Each algae panel absorbs 0.5 $kgCO_{2eq}$ for each week in accordance with the research developed by Kim K. about the requalification of the main building of University of North Caroline at Charlotte Campus. From this paper it was also calculated a value for the embodied emissions of an algae façade and it was employed even if it is not probably the same for Norway. But the lack of data and research about this application led to this solution. The analyses of the embodied emissions related to this technology and its application could represent a future development of this work. The algae panel were applied to the southern façade at the first level which was not covered by the shell. The outer wall's surface is approximately 30.0 m^2 not including the windows. Taking into account the lower efficieny of this system, it was necessary to apply at least 23.0 m^2 of green algae in order to satisfy the domestic water's demand as the solar thermal collectors did. Thus, it was covered the façade with five panel 1.3 m long and 4.0 m high. The consequent area is 26.0 m^2 and it guaranteed a total CO_2 reduction of 1.46 $kgCO_{2eq}/m^2BRA$ year. This reduction is the sum of two components which are the contribution from the electricity production and the one from the assimilation of CO_2. Maintaining the same surface of BIPV previously evaluated and integrating it with the five algae panels, the E_e turned out to be increased from 11.98 $kgCO_{2eq}/m^2BRA$ year to 12.75 $kgCO_{2eq}/m^2BRA$ year with a variation of 6.4 %. On the other hand, the improvement of the active systems allowed to reach a value of CO_2 reduction of 24.60 $kgCO_{2eq}/m^2BRA$ year instead of 23.10 $kgCO_{2eq}/m^2BRA$ year. The positive mismatch between emissions and their reduction is 2.16 $kgCO_{2eq}/m^2BRA$ year as reported on Figure 77. Actually, the ZEB - OM ambition level can be achieved also with a lower quantity of solar cells. The graph on Figure 76 demonstrates it and highlights the trend of the emission balance depending on the surface of BIPV. Tha algae panels were maintained constant as the solar thermal on the previous stages. The exploitation of the whole available surface for the BIPV in addition to the five algae panels allowed to reach a value of CO_2 reduction higher than 30.00 $kgCO_{2eq}/m^2BRA$ year which led to the improvement of the maximum of the potentiality explored on the previous concept. This last configuration with a 173.0 m^2 of photovoltaic and 26.0 m^2 of algae panels was able to guarantee a positive mismatch of 6.51 $kgCO_{2eq}/m^2BRA$ year due to its reduction of 30.39 $kgCO_{2eq}/m^2BRA$ year and its emissions of 23.88 $kgCO_{2eq}/m^2BRA$ year. In conclusion, these two improved concepts seem to be not particularly different, thus it was done a reasoning similar to the one did about the materials: the model selected as the last model of the evolutionary lineage describes in this master thesis is the one characterized by a better reliability of the embodied emissions. It led to the exclusion of the model with the algae panel because its database is from U.S.A. and probably is not adapt for being applied integrally in Europe.

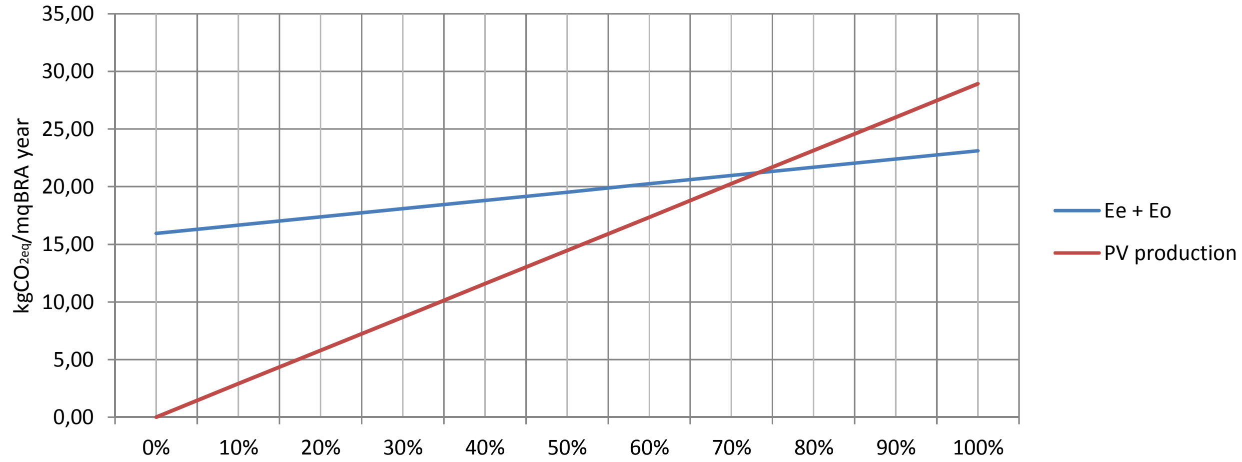


Figure 76 Variation of the emission balance depending on the percentuage of available surface covered by PV. The quantity of Algae panel was maintained constant.

surface available	*PV*	*m^2*	173.0									
	AP	*m^2*	30.0									
PV surface		*%*	10.0	20.0	30.0	40.0	50.0	60.0	70.0	80.0	90.0	100.0
		m^2	17.3	34.6	51.9	69.2	86.5	103.8	121.1	138.4	155.7	173.0
*PV production**			2.90	5.80	8.70	11.60	14.50	17.40	20.20	23.10	26.00	28.90
Algae Panel		*n*	1	2	3	4	5	6	7	8	9	10
		m^2	5.2	10.4	15.6	20.8	26.0	31.2	36.4	41.6	46.8	52.0
*AP production**			0.13	0.25	0.38	0.51	0.63	0.76	0.89	1.02	1.14	1.27
*CO_2 absorbed**			0.17	0.33	0.50	0.66	0.83	1.00	1.16	1.33	1.49	1.66
*tot CO_2 reduction**			4.36	7.25	10.14	13.03	15.93	18.82	21.71	24.60	27.50	30.39
*E_e**			7.72	8.44	9.16	9.88	10.59	11.31	12.03	12.75	13.47	14.18
*E_o**			9.7									
*E_e+ E_o**			17.42	18.14	18.86	19.58	20.29	21.01	21.73	22.45	23.17	23.88
*balance**			- 13.0	- 10.9	- 8.7	- 6.5	- 4.4	- 2.2	0.0	2.2	4.3	6.5

* the unit considered is $kgCO_{2eq}/m^2$ year which is evaluated based on a building's lifetime of 60 years and a BRA of 160 square meters.

Table 33 Variation of the emission balance depending on the percentuage of available surface covered by PV. The quantity of Algae panel was maintained constant.

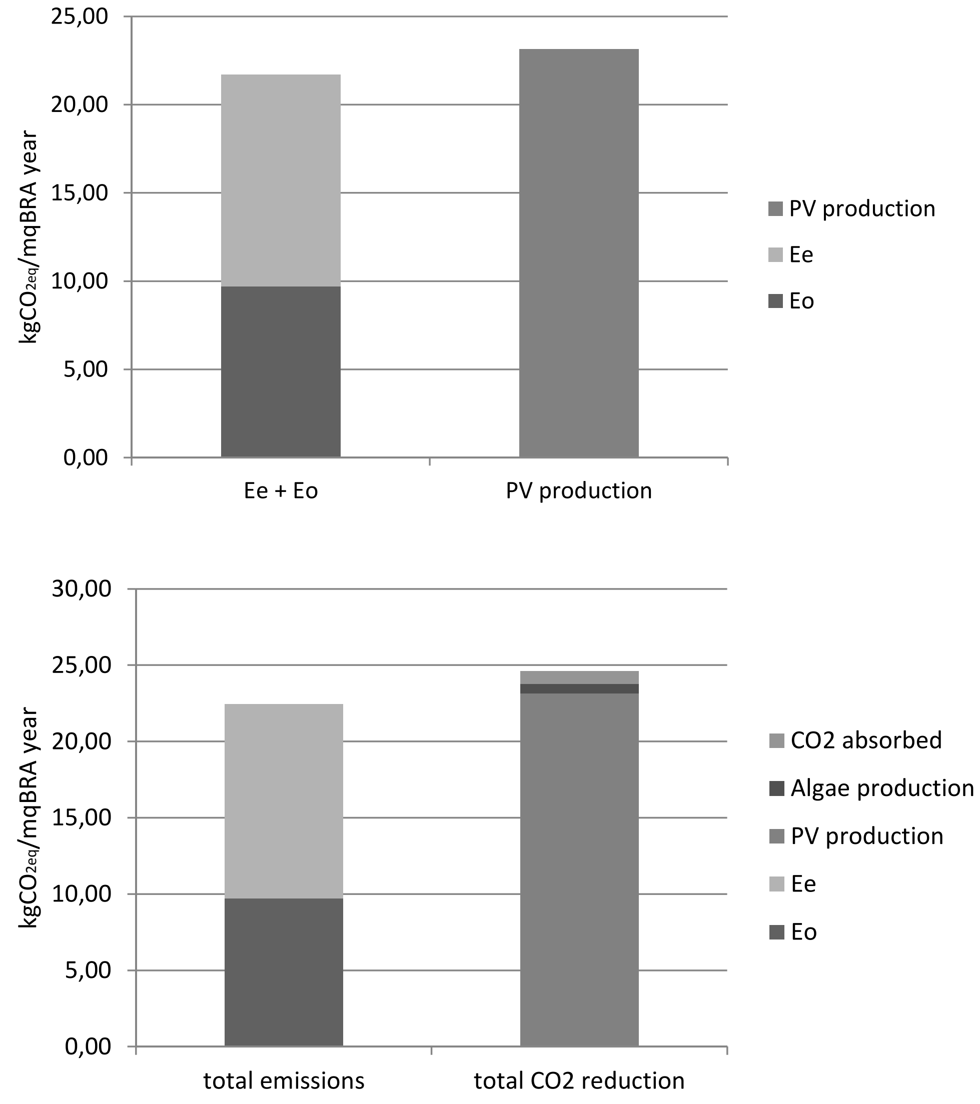


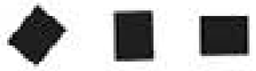
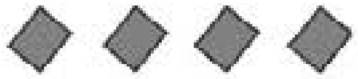
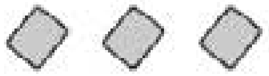
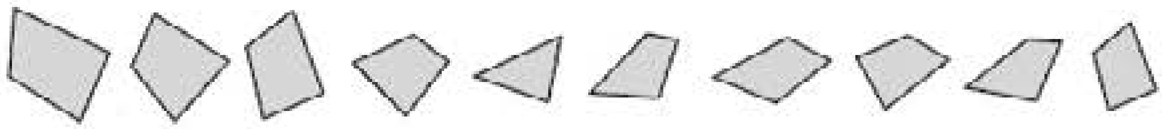
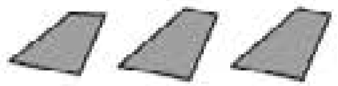
Figure 77 Emission balances of the final active model with improved BIPV system and the one with the Algae panels on façades.

6. CONCLUSION

Through this analysis and optimization process with parametric software is possible to realize important considerations about method and results according to the initial research questions. The operational emissions can influence through building's properties. As a matter of fact stage 6 of active approach presents an optimized shape for solar radiation and LCA but the new configuration is not regular than the first in passive approach (stage 1-3) and this is why there are more heat losses, a direct effect is the increase of the energy consumption. In this case the building orientation is not important for the increase of the total solar radiation average but a correct distribution of internal spaces with a correct orientation could condition the consumptions in a positive way. Moreover the choice of materials is fundamental, the wood results to be the highest performing material: the thermal properties with insulation are very good for heat losses reduction and it is the best for the LCA evaluation (embodied emission).
For the study the best result for passive approach is represented by stage 3, the Ee are 73 739 kgCO2eq and increasing the PV surface on the South-exposed façades is possible to achieve the ZEB - OM level, the analysis shows that the 40 % of surface should be covered with PV. In fact this stage is located between the two different approaches examinated, the employment of more PV panel is the beginnings of active strategies. The emissions are reduced from the base case, the initial value of emissions is 80 225 kgCO2eq.
On the other hand the active approach with Model 6 has a value of emissions higher, Ee = 87 422 kg CO2eq, the double skin envelope increased the total emissions and the shape of the building increased the heat losses. However model 6 presents a roof with two different inclinations and this configuration permitted the best performance of PV because the exposure is optimized.
The solar radiation caught by the final roof is 116 806 kWh/year while the value for the flat roof is 83 210 kWh/year. In the next scheme are represented in detail the advantage and disadvantages for each model and each approach.
The main goal remains the effectiveness of the developed method and its application to ZEB. The parametric approach permits to control many aspects of the project, which can be modified simultaneously. With the variation of a single parameter, which for example is into the analysis of the LCA or the weather file for the total solar radiation, the results and the optimization processes are immediately visible. It becomes easier to experiment different solutions, the response is immediate. It can be possible to choose step by step the algorithm, type of analysis, the parameter to be changed or to be optimized. In this research in the active approach it was studied the better roof configuration for PV panels in Oslo and in Perugia, then with another weather data. Perugia is located in the centre of Italy and the climate conditions and sun exposure are different from Oslo; in fact in the final models there is difference between the roof inclination, in the both cases the final roof for SR is not flat, but the angle of inclination changes, according to with the specific sun-path.
Each latitude with each weather file influenced the shape of the responsive model. A different climate condition changes also the energy demand for the operational phase and the EPD data for LCA evaluation; but with our parametric algorithm the check is simple for all point of view. In a research It is important to underlines also the boundaries, especially for future development. The parametric modeling with the possibility to control each parameter should be not easy when the geometry of the building is more complicated than a simple box like ZEB project. Probably a compromise between the advantages of active and passive strategies respectively it should be the best solution for a design process.
Furthermore the LCA analysis might become more specific with an accurate data for each zones, now a lot of materials, especially the new ones, have not a certain value of embodied emissions. Exact value produces a precise analysis and it is fundamental for a sustainable future, at last finally carbon free.

Passive Strategies

Active Strategies

Stage	Shapes	ADVANTAGES	DISADVANTAGES
Stage 0			
Stage 1		The total SR average remained the same by changing the orientation. The average on two contiguous façades was increased. Main axis rotated by 51 degrees.	The longest ssurface was not oriented completely toward South.
Stage 2		The model was managed by applying a parametric approach. The algorithm controlled the modules' dimensions, arrangement and rotation. The parametric façades were just the ones Southward. The emissions were reduced by improving the material performance. Modules 60 by 60 E_e = 78 527 kg$CO_{2\ eq}$ Emissions' reduction: - 2.14 %	The daylighting evaluation turned out to be not completely satisfying.
Stage 3		The algorithm permitted to developed a tessellation of the façades by using the Substrate component of GH. It allowed to have a better control of the DF and guaranteed an improved LCA. E_e = 73 739 kg$CO_{2\ eq}$ DF = 2.52 %	It was necessary to increase the PV surface in order to reach the ZEB - OM level. The 40.0 % of the South-exposed façades should be covered by BIPV system for achieving the ZEB - OM level.
Stage 4		It is the first approach to the shape's change in order to generate an environmentally responsive model. The deformed box generated for being placed in Oslo reached a SR average of 584 kWh/m^2 year.	The results of the optimization process did not permit to reach any improvement because they were still too influenced by the initial shape. The SR caught by the optimized envelope in Oslo was 195 960 584 kWh/year.
Stage 5		The modification of the algorithm permitted to reduce the influence of the initial box. It generated a series of models with high performance in terms of SR. The best model was able to catch 336 600 kWh/year.	The form generated by Octopus needed to be modified in order to design a comfortable space.
Stage 6		The final configuration was regular thanks to a double skin system which permitted to exploit as much as possible the optimized envelope and its exposure. SR caugth by the final roof: 116 806 kWh/year SR caugth by the initial roof: 83 210 kWh/year	The double skin envelope increased the emissions and the heat lossess through the envelope. It was necessary a larger BIPV's area. Stage 0: E_e = 80 373 kg$CO_{2\ eq}$ Stage 6: E_e = 87 422 kg$CO_{2\ eq}$ BIPV surface necessary for achieving ZEB - OM level: 121.0 m^2

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